U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

Ground-Water, Surface-Water, and Water-Chemistry Data, Black Mesa Area, Northeastern Arizona—1999

Open-File Report 00–453

Prepared in cooperation with the
BUREAU OF INDIAN AFFAIRS and the
ARIZONA DEPARTMENT OF WATER RESOURCES

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By Blakemore E. Thomas *and* Margot Truini

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Tucson, Arizona
2000

U.S. DEPARTMENT OF THE INTERIOR
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CONVERSION FACTORS

Multiply	By	To obtain
inch (in)	2.54	centimeter
inch (in)	25.4	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer
acre-foot (acre-ft)	0.001233	cubic hectometer
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
gallon per minute (gal/min)	0.06309	liter per second
gallon per day (gal/d)	0.003785	cubic meter per day

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F=(1.8°C)+32$$

ABBREVIATED WATER-QUALITY UNITS

Chemical concentration and water temperature are given only in metric units. Chemical concentration in water is given in milligrams per liter (mg/L) or micrograms per liter (µg/L). Milligrams per liter is a unit expressing the solute mass (milligrams) per unit volume (liter) of water. One thousand micrograms per liter is equivalent to 1 milligram per liter. For concentrations less than 7,000 milligrams per liter, the numerical value is about the same as for concentrations in parts per million. Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25°C).

VERTICAL DATUM

Sea level: In this report, “sea level” refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—A geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929. **Altitude**, as used in this report, refers to distance above or below sea level.

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Abstract

The N aquifer is the major source of water in the 5,400-square-mile area of Black Mesa in northeastern Arizona. Availability of water is an important issue in this area because of continued industrial and municipal use, a growing population, and a precipitation of only about 6 to 12 inches per year.

The monitoring program in Black Mesa has been operating since 1971 and is designed to determine the long-term effects of ground-water withdrawals from the N aquifer for industrial and municipal uses. The monitoring program includes measurements of (1) ground-water pumping, (2) ground-water levels, (3) spring discharge, (4) surface-water discharge, and (5) ground-water chemistry.

In 1999, total ground-water withdrawals were 7,110 acre-feet, industrial use was 4,210 acre-feet, and municipal use was 2,900 acre-feet. From 1998 to 1999, total withdrawals increased by 0.7 percent, industrial use increased by 4 percent, and municipal use decreased by 4 percent.

From 1998 to 1999, water levels declined in 11 of 15 wells in the unconfined part of the aquifer, and the median decline was 0.7 foot. Water levels declined in 14 of 16 wells in the confined part of the aquifer, and the median decline was 1.2 feet.

From the prestress period (prior to 1965) to 1999, the median water-level decline in 31 wells was 10.6 feet. Median water-level changes were 0.0 foot for 15 wells in the unconfined part of the aquifer and -45.5 feet in 16 wells in the confined part.

From 1998 to 1999, discharges were measured annually at four springs. Discharges declined 30 percent and 3 percent at 2 springs, did not change at 1 spring, and increased by 11 percent at 1 spring. For the past 10 years, discharges from the four springs have fluctuated; however, an increasing or decreasing trend was not observed.

Continuous records of surface-water discharge have been collected from July 1976 to 1999 at Moenkopi Wash, July 1996 to 1999 at Laguna Creek, June 1993 to 1999 at Dinnebito Wash, and April 1994 to 1999 at Polacca Wash. Median flows for November, December, January, and February of each water year are used as an index of ground-water discharge to those streams. Increasing or decreasing trends are not apparent in these median winter flows for the periods of record.

In 1999, water samples were collected from 12 wells and 4 springs and analyzed for selected chemical constituents. Dissolved-solids concentrations ranged from 91 to 630 milligrams per liter. Water samples from 10 of the wells and the 4 springs had less than 350 milligrams per liter of dissolved solids. Water-chemistry data are available for nine wells and four springs from about

the mid-1980's. For that time period, the data from those sites have remained fairly stable. From 1987 to 1999, concentrations of dissolved solids, chloride, and sulfate may have increased slightly in samples from Moenkopi School Spring.

INTRODUCTION

The Black Mesa area includes about 5,400 mi^2 in northeastern Arizona (fig. 1) and has a diverse topography that includes flat plains, mesas, and incised drainages. Black Mesa is about 2,000 mi^2, is bounded by 2,000-foot cliffs on the north and northeast sides, and slopes gradually downward to the south and southwest. Availability of water is an important issue in the study area because of continued ground-water withdrawals, a growing population, and an annual precipitation that averages only about 6 to 12 in.

The N aquifer is the major source of water for industrial and municipal uses in the Black Mesa area. The N aquifer consists of three formations—the Navajo Sandstone, the Kayenta Formation, and the Lukachukai Member[1] of the Wingate Sandstone, which are hydraulically connected and function as a single aquifer (fig. 2). Peabody Western Coal Company is the principal industrial user of water, and the Navajo Nation and Hopi Tribe are the principal domestic and municipal users.

Withdrawals from the N aquifer in the Black Mesa area have been increasing during the last 30 years (table 1). Peabody Western Coal Company began operating a strip mine in the northern part of the mesa in 1968. The quantity of water pumped by the company increased from about 100 acre-ft in 1968 to a maximum of 4,740 acre-ft in 1982. About 4,210 acre-ft of water was pumped in 1999. Withdrawals for municipal use from the N aquifer have increased steadily from an estimated 250 acre-ft in 1968 to 2,900 acre-ft in 1999.

The Navajo Nation and the Hopi Tribe have been concerned about the long-term effects of withdrawals from the N aquifer on available water supplies, on stream and spring discharge, and on ground-water chemistry. In 1971, these concerns led to the establishment of a monitoring program of the water resources in Black Mesa by the U.S. Geological Survey (USGS) in cooperation with the Arizona Department of Water Resources (ADWR). In 1983, the Bureau of Indian Affairs (BIA) joined the cooperative effort. Since 1983, the Navajo Tribal Utility Authority (NTUA); Peabody Western Coal Company; the Hopi Tribe; and the Western Navajo Agency, Chinle Agency, and Hopi Agency of the BIA have assisted in the collection of hydrologic data.

Purpose and Scope of the Report

This report presents the results of ground-water, surface-water, and water-chemistry monitoring in the Black Mesa area generally from January to December 1999. The monitoring is designed to determine the effects of industrial and municipal pumpage from the N aquifer on ground-water levels, stream and spring discharge, and water chemistry. Continuous and periodic data are collected for ground water and surface water. Ground-water data include pumpage, water levels, spring discharges, and water chemistry. Surface-water data include discharges at four continuous-record streamflow-gaging stations.

Previous Investigations

Seventeen progress reports on the monitoring program for the Black Mesa area have been prepared by the USGS (U.S. Geological Survey, 1978; G.W. Hill, hydrologist, written commun., 1982, 1983; Hill, 1985; Hill and Whetten, 1986; Hill and Sottilare, 1987; Hart and Sottilare, 1988, 1989; Sottilare, 1992; Littin, 1992, 1993; Littin and Monroe, 1995a, 1995b, 1996, 1997; Littin and others, 1999; Truini and others, 2000). Most of the data from the monitoring program are contained in these reports, except for continuous stream-discharge and periodic water-quality data from

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[1]The name Lukachukai Member was formally abandoned by Dubiel (1989) and is used herein for report continuity in the monitoring program as it relates to that part of the Wingate Sandstone included in the N aquifer.

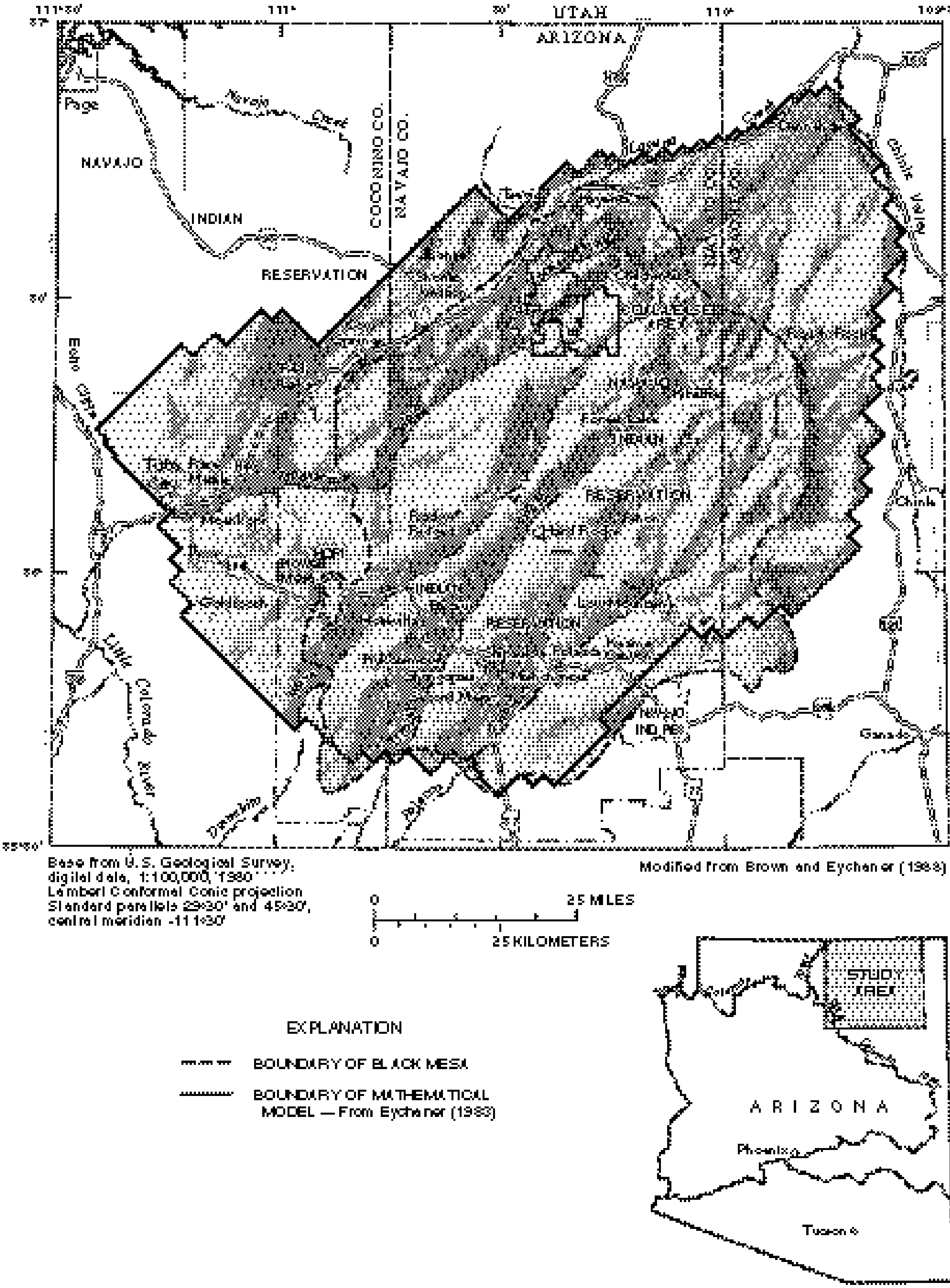
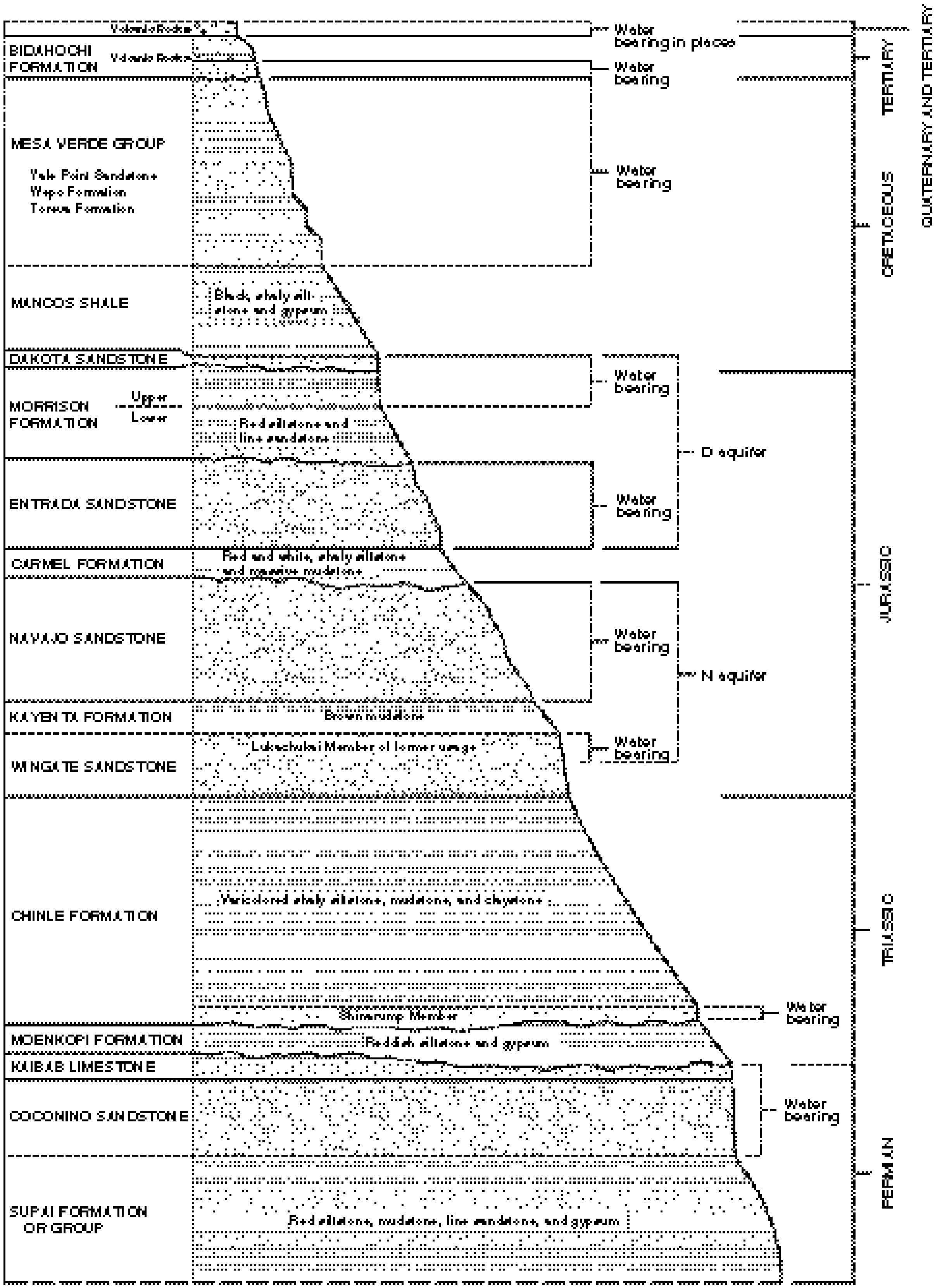


Figure 1. Location of study area.



Modified from Harshbarger and others (1966)

Figure 2. Rock formations and hydrogeologic units of the Black Mesa area, Arizona. The N aquifer is approximately 1,000 feet thick.

Table 1. Withdrawals from the N aquifer, Black Mesa area, Arizona, 1965–99

[Values are rounded to nearest 10 acre-feet. Data for 1965–79 from Eychaner (1983). Total withdrawals in Littin and Monroe (1996) were for the confined part of the aquifer]

Year	Industrial[1]	Municipal[2,3]		Total withdrawals	Year	Industrial[1]	Municipal[2,3]		Total withdrawals
		Confined	Unconfined				Confined	Unconfined	
1965	0	50	20	70	1983	4,460	1,360	1,280	7,100
1966	0	110	30	140	1984	4,170	1,070	1,400	6,640
1967	0	120	50	170	1985	2,520	1,040	1,160	4,720
1968	100	150	100	350	1986	4,480	970	1,260	6,710
1969	40	200	100	340	1987	3,380	1,130	1,280	6,240
1970	740	280	150	1,170	1988	4,090	1,250	1,310	6,650
1971	1,900	340	150	2,390	1989	3,450	1,070	1,400	5,920
1972	3,680	370	250	4,300	1990	3,430	1,170	1,210	5,810
1973	3,520	530	300	4,350	1991	4,020	1,140	1,300	6,460
1974	3,830	580	360	4,770	1992	3,820	1,180	1,410	6,410
1975	3,500	600	510	4,610	1993	3,700	1,250	1,570	6,520
1976	4,180	690	640	5,510	1994	4,080	1,210	1,600	6,890
1977	4,090	750	730	5,570	1995	4,340	1,220	1,510	7,070
1978	3,000	830	930	4,760	1996	4,010	1,380	1,650	7,040
1979	3,500	860	930	5,290	1997	4,130	1,380	1,580	7,090
1980	3,540	910	880	5,330	1998	4,030	1,440	1,590	7,060
1981	4,010	960	1,000	5,970	1999	4,210	1,420	1,480	7,110
1982	4,740	870	960	6,570					

[1]Metered pumpage from the confined part of the aquifer by Peabody Western Coal Company.
[2]Does not include withdrawals from the wells equipped with windmills.
[3]Includes estimated pumpage, 1965–73, and metered pumpage, 1974–79, at Tuba City; metered pumpage at Kayenta and estimated pumpage at Chilchinbito, Rough Rock, Piñon, Keams Canyon, and Kykotsmovi before 1980; metered and estimated pumpage furnished by the Navajo Tribal Utility Authority and the Bureau of Indian Affairs and collected by the U.S. Geological Survey, 1980–85; and metered pumpage furnished by the Navajo Tribal Utility Authority, the Bureau of Indian Affairs, various Hopi Village Administrations, and the U.S. Geological Survey, 1986–99.

Moenkopi Wash collected before the 1986 water year; those data were published in U.S. Geological Survey (1963–64a, b; 1965–74a, b; 1976–83); White and Garrett (1984, 1986, 1987, 1988); Boner and others (1989, 1990, 1991, 1992); Smith and others (1993, 1994, 1995, 1996, 1997); and Tadayon and others (1998, 1999). Before the monitoring program, a large data-collection effort resulted in a compilation of well and spring data for the Navajo and Hopi Indian Reservations (Davis and others, 1963).

Many interpretive studies have been done in the Black Mesa area. Cooley and others (1969) made the first comprehensive evaluation of the regional hydrogeology of the Black Mesa area. Eychaner (1983) developed a two-dimensional mathematical model of ground-water flow in the N aquifer. A few years later, Brown and Eychaner (1988) converted the model to a new program and a finer spatial grid, revised estimates of selected aquifer characteristics, and recalibrated the model. GeoTrans, Inc. (1987) also developed a two-dimensional model of the N aquifer in the 1980’s. Waterstone Environmental Hydrology and Engineering (1995) conducted a sensitivity analysis of the models by Brown and Eychaner (1988) and GeoTrans, Inc. (1987). In the late 1990’s, HSIGeoTrans, Inc. and Waterstone Environmental Hydrology and Engineering, Inc. (1999) developed a detailed three-dimensional mathematical model of the D and N aquifers.

Kister and Hatchett (1963) made the first comprehensive evaluation of the chemistry of water from wells and springs in the Black Mesa area. HSIGeoTrans, Inc. (1993) evaluated the major-ion and isotopic chemistry of the D and N aquifers. Lopes and Hoffmann (1997) analyzed ground-water ages, recharge, and hydraulic conductivity of the N aquifer using geochemical techniques. Zhu and others (1998) estimated ground-water recharge using isotopic data and flow estimates from the model developed by GeoTrans, Inc. (1987).

HYDROLOGIC DATA

In 1999, the Black Mesa monitoring program included metering and estimating ground-water withdrawals, measuring depth to ground water, measuring discharge in streams and springs, and collecting and analyzing water samples from wells and springs. Ground-water withdrawals from 34 well systems, water levels at 6 observation wells, and surface-water discharge at 4 sites were monitored continuously. Discharge at 4 springs and ground-water levels at 25 wells were measured annually. Spring discharges were measured in December 1999. Ground-water levels were measured between October 1999 and February 2000. The goal was to measure all ground-water levels between October and December 1999; however, adverse weather conditions forced a delay and 11 wells were measured in January or February 2000. Water samples were collected from 12 wells and 4 springs in December 1999 or January 2000 and analyzed for chemical constituents. Identification and location information for the 42 wells used for water-level measurements and water-quality sampling is shown in table 2.

Withdrawals from the N Aquifer

Withdrawals from the N aquifer are separated into three categories—(1) industrial use from the confined part of the aquifer, (2) municipal use from the confined part of the aquifer, and (3) municipal use from the unconfined part of the aquifer (table 1, fig. 3). The industrial category includes eight wells at the well field of Peabody Western Coal Company in northern Black Mesa (fig. 4). The Bureau of Indian Affairs, Navajo Tribal Utility Authority, and Hopi Tribe operate about 70 municipal wells. Withdrawals from the N aquifer were compiled primarily on the basis of metered data (tables 1 and 3).

Withdrawals from wells equipped with windmills are not measured in this monitoring program. About 270 windmills in the Black Mesa area withdraw water from the D and N aquifers, and estimated total withdrawals by the windmills are about 65 acre-ft/yr (HSIGeoTrans, Inc., and Waterstone Environmental Hydrology and Engineering, Inc., 1999). This amount is less than 1 percent of the total annual withdrawal from the N aquifer.

In 1999, the total ground-water withdrawal from the N aquifer was about 7,110 acre-ft (table 1), which is a 0.7-percent increase from the total withdrawal in 1998. Withdrawals for municipal use from the confined part of the aquifer were 1,420 acre-ft, which is a 1-percent decrease from 1998. Withdrawals for municipal use from the unconfined part of the aquifer were 1,480 acre-ft, which is a 7-percent decrease. Withdrawals for industrial use were 4,210 acre-ft, which is a 4-percent increase from 1998.

Withdrawals from the N aquifer have been increasing since the 1970’s (table 1, fig. 3). Total withdrawals increased from 1,170 acre-ft in 1970 to 4,300 acre-ft in 1972 when industrial use increased from 740 to 3,680 acre-ft. Since 1973, industrial use has fluctuated between 2,500 and 4,700 acre-ft/yr. Municipal use increased by about 20 percent per year during the 1970’s, slowed to an increase of about 4 percent per year in the 1980’s, and slowed further to an increase of about 2 percent per year in the 1990’s. From 1998 to 1999, industrial use increased by 4 percent, and municipal use decreased by 4 percent.

In the 1970’s, industrial use was about 75 percent of the total withdrawal. With the increase in municipal use over the last 30 years, industrial use, as a percentage of total withdrawals, has declined to about 60 percent in the late 1990’s.

During an evaluation of historical pumpage data, a mistake was discovered in the reported pumpage for the Tuba City NTUA wells. The NTUA records for 1991 had a misplaced decimal place for the meter readings at one well, which resulted in estimated withdrawal of 10 times greater than actual withdrawal for that well. In this report, therefore, the total municipal use for unconfined areas in 1991 was changed from 3,360 to 1,300 acre-ft, and total withdrawal was changed from 8,520 to 6,460 acre-ft (table 1, fig. 3).

In an effort to improve and ensure accuracy of ground-water withdrawal data, a quality-assurance program was begun in 1985 for data from industrial and municipal wells completed in the N aquifer. Nearly all industrial and municipal wells in the study area are equipped with totalizing flowmeters to measure ground-water withdrawals.

Table 2. Identification numbers, names, and locations of study wells, Black Mesa area, Arizona

[Dashes indicate no data]

U.S. Geological Survey identification number	U.S. Geological Survey well location	Common name or location	Bureau of Indian Affairs site number	Latitude (degrees, minutes, seconds)	Longitude (degrees, minutes, seconds)
355023110182701	094-03.23x11.05	Keams Canyon PM2	---	355025	1101827
355215110375001	095-07.28x08.90	Kykotsmovi PM2	---	355212	1103742
355230110365801	095-06.50x08.61	Kykotsmovi PM1	---	355232	1103657
355236110364501	095-06.34x08.54	Kykotsmovi PM3	---	355235	1103645
355648110475501	096-02.73x03.65	Howell Mesa	6H-55	355649	1104754
360055110304001	075-00.61x16.21	BM observation well 5	4T-519	360051	1103041
360217111122601	077-11.59x14.61	Tuba City	3K-325	360217	1111226
360418110352701	075-05.09x12.30	Rocky Ridge PM2	---	360418	1103527
360614110130801	073-12.26x10.09	Piñon PM6	---	360610	1101315
360734111144801	077-13.77x08.52	Tuba City	3T-333	360734	1111448
360904111140201	077-13.05x06.81	Tuba City NTUA 1	3T-508	360904	1111402
360918111080701	077-07.55x06.55	Tuba City Rare Metals 2	---	360918	1110807
360953111142401	077-13.38x05.87	Tuba City NTUA 4	3T-546	360954	1111425
361225110240701	074-08.95x02.95	BM observation well 6	---	361228	1102436
361737110180301	056-02.85x14.19	Forest Lake NTUA 1	4T-523	361737	1101801
361832109462701	054-01.35x13.20	Rough Rock	10T-258	361832	1094627
361933110565001	058-11.04x12.16	Red Lake PM1	---	361924	1105654
362043110030501	---	Kitsillie NTUA 2	---	362043	1100305
362149109463301	054-01.47x09.39	Rough Rock	10R-111	362149	1094633
362406110563201	058-10.73x06.78	White Mesa Arch	1K-214	362406	1105632
362418109514601	054-06.30x06.52	Rough Rock PM5	---	362420	1095146
362456110503001	058-05.09x05.82	Cow Springs	1K-225	362456	1105030
362647110243501	056-09.00x03.73	Peabody 4	---	362647	1102437
362823109463101	054-01.41x01.85	Rough Rock	10R-119	362823	1094631
362936109564101	054-10.96x00.63	BM observation well 1	8T-537	362927	1095651
363005110250901	039-09.44x17.18	Peabody 2	---	363005	1102509
363013109584901	037-12.81x16.98	Sweetwater Mesa	8K-443	363013	1095849
363103109445201	036-13.75x16.01	Rough Rock	9Y-95	363103	1094452
363137110044702	038-04.43x15.39	Chilchinbito PM3	---	363137	1100447
363143110355001	040-05.38x15.27	BM observation well 4	2T-514	363141	1103554
363213110342001	040-04.03x14.68	Shonto Southeast	2K-301	363213	1103420
363232109465601	037-01.81x14.35	Rough Rock	9Y-92	363232	1094656
363309110420501	040-11.20x13.60	Shonto	2K-300	363309	1104205
363423110305501	040-00.85x12.17	Shonto Southeast	2T-502	363423	1103055
363727110274501	039-11.83x08.69	Long House Valley	8T-510	363727	1102745
363850110100801	038-09.40x07.08	BM observation well 2	8T-538	363850	1101012
364034110240001	039-08.31x05.09	Marsh Pass	8T-522	364034	1102400
364226110171701	039-02.11x02.94	Kayenta West	8T-541	364226	1101717
364248109514601	037-06.23x02.51	Northeast Rough Rock	8A-180	364248	1095146
364338110154601	039-00.70x01.57	BM observation well 3	8T-500	364338	1101545
364344110151201	039-00.17x01.45	Kayenta PM2	8A-295	364345	1101459
365045109504001	022-05.23x10.58	Dennehotso PM2	8K-521	365054	1095034

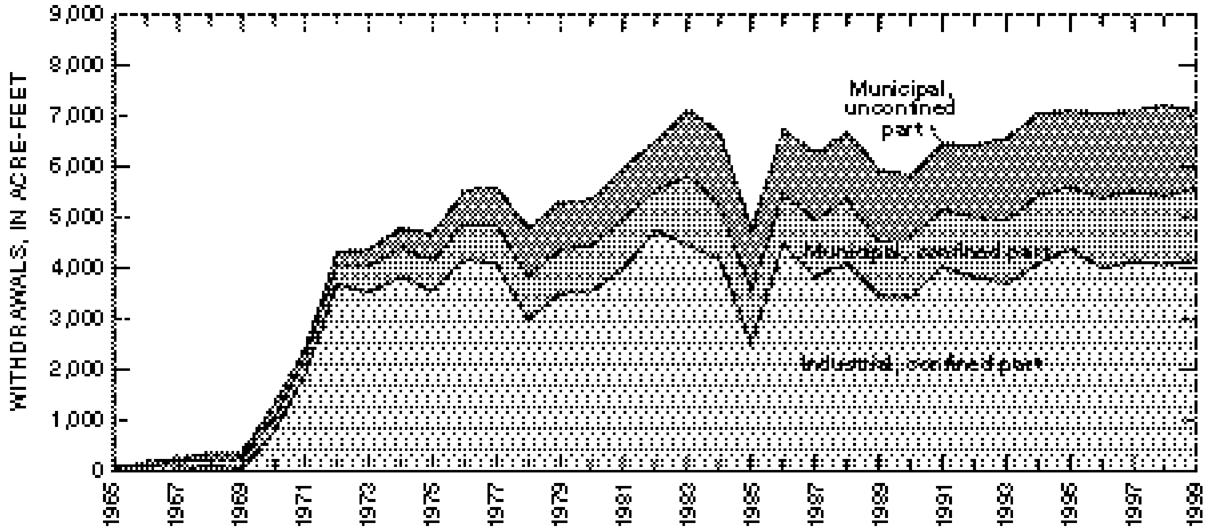


Figure 3. Withdrawals from the N aquifer, Black Mesa area, Arizona, 1965–99.

The flowmeters on the wells are tested about once every 5 years by measuring pumpage with a calibrated mechanical flowmeter and comparing the measured pumpage to the metered pumpage. For the purpose of this study, the allowable difference between the discharge measured by the permanent totalizing flowmeter and the test meter is 10 percent.

This flowmeter testing was performed on about half the municipal wells in 1998 and early 1999, and results from that testing are shown in Truini and others (2000). Most of the remaining municipal wells were tested in 1999, and those results are shown in this report. Some municipal wells were not tested in 1998 or 1999. Most of the untested wells had been taken out of service. At one well, the flowmeter could not be connected; and at one well, the pumpage exceeded the capacity of the test meter.

For this report, 25 municipal wells were tested using a calibrated Rockwell mechanical flowmeter. The test flowmeter was attached to the discharge bypass at each site, and the average was taken of three readings made after discharge stabilized. The flowmeter measurements then were compared to the meter readings of the permanent totalizing flowmeter (table 4). Twenty-four of the 25 tested wells had permanent flowmeter readings within the allowable 10-percent difference from the test flowmeter (table 4). The meters at one well had a difference of 12.2 percent.

Ground-Water Levels in the N Aquifer

Ground water in the N aquifer is under confined conditions in the central part of the study area and under unconfined or water-table conditions around the periphery (fig. 5). The ground water generally flows radially outward from recharge areas near Kayenta and Shonto to the southwest, south, southeast, and east (Lopes and Hoffmann, 1997).

Ground-water levels are measured each year of the Black Mesa monitoring program and compared with levels from previous years to determine changes over time. In 1999, water levels were measured in 31 wells that are used for observation, municipal supply, or stock supply (table 5). Six of the 31 wells are observation wells that were operated on a continuous basis; water levels were recorded daily. Water levels were measured manually twice a year in the six continuous-observation wells.

The wells used for water-level measurements are spread throughout the study area (fig. 5). Although all the wells are completed in the N

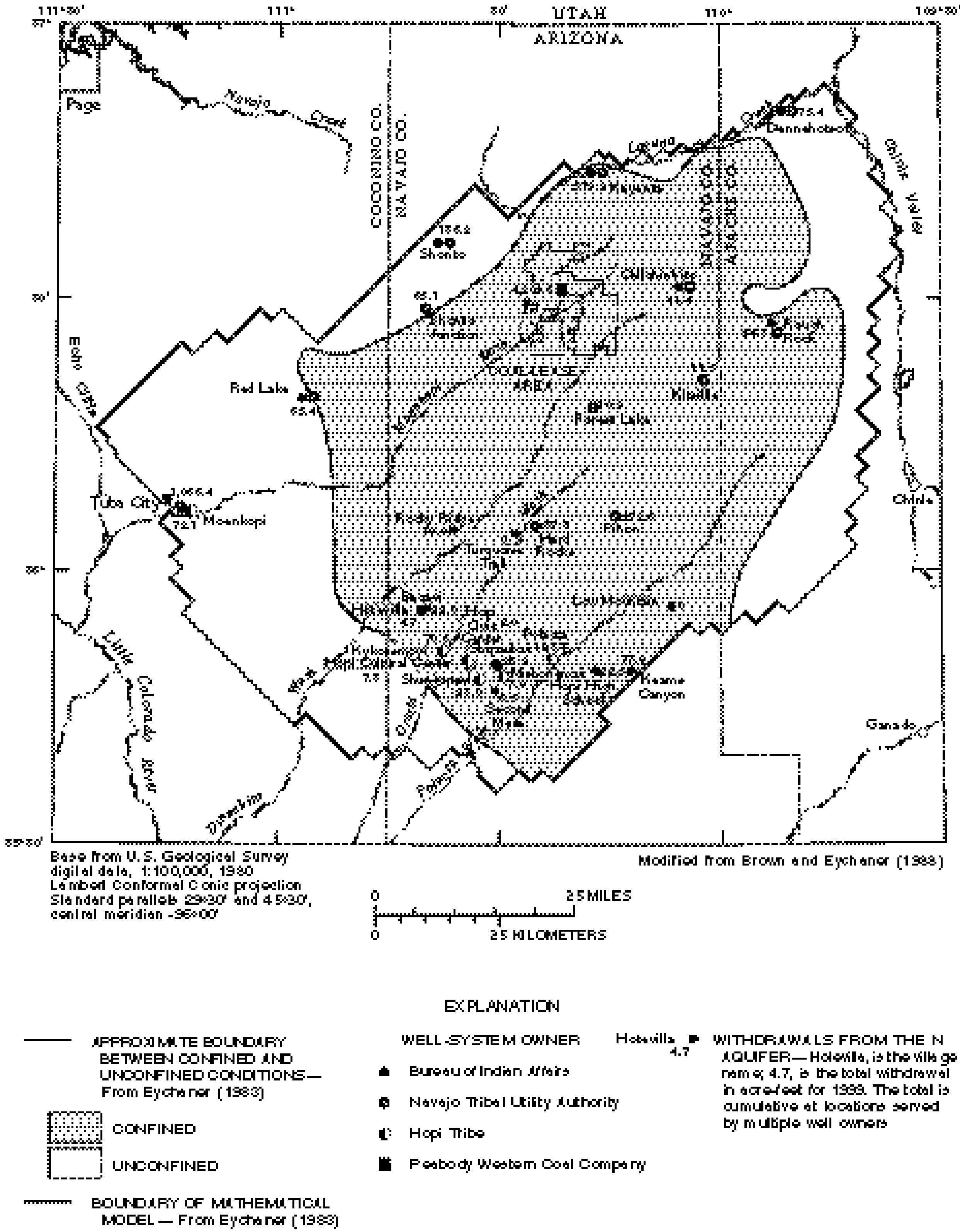


Figure 4. Location of well systems monitored for withdrawals from the N aquifer, Black Mesa area, Arizona, 1999.

Table 3. Withdrawals from the N aquifer by well system, Black Mesa area, Arizona, 1999

[Withdrawals, in acre-feet, are from flowmeter measurements. BIA, Bureau of Indian Affairs; NTUA, Navajo Tribal Utility Authority; USGS, U.S. Geological Survey; Peabody, Peabody Western Coal Company; Hopi, Hopi Village Administrations; BIA Roads, Bureau of Indian Affairs, Division of Roads]

Well system (one or more wells)	Owner	Source of data	Withdrawals	
			Confined aquifer	Unconfined aquifer
Chilchinbito	BIA	USGS/BIA	6.8	
Dennehotso	BIA	USGS/BIA		41.8
Hopi High School	BIA	USGS/BIA	22.5	
Hotevilla	BIA	USGS/BIA	4.7	
Kayenta	BIA	USGS/BIA	75.7	
Keams Canyon	BIA	USGS/BIA	77.0	
Low Mountain	BIA	USGS/BIA	[1]0	
Piñon	BIA	USGS/BIA	[1]0	
Red Lake	BIA	USGS/BIA		7.6
Rocky Ridge	BIA	USGS/BIA	11.3	
Rough Rock	BIA	USGS/BIA	34.6	
Second Mesa	BIA	USGS/BIA	6.5	
Shonto	BIA	USGS/BIA		119.8
Tuba City	BIA	USGS/BIA		194.1
Turquoise Trail	BIA	BIA Roads	[1]0	
Chilchinbito	NTUA	NTUA	34.6	
Dennehotso	NTUA	NTUA		33.6
Forest Lake	NTUA	NTUA	10.9	
Hard Rock	NTUA	NTUA	37.3	
Kayenta	NTUA	NTUA	504.2	
Kitsillie	NTUA	NTUA	11.5	
Piñon	NTUA	NTUA	272.6	
Red Lake	NTUA	NTUA		57.8
Rough Rock	NTUA	NTUA	22.2	
Shonto	NTUA	NTUA		16.4
Shonto Junction	NTUA	NTUA		65.1
Tuba City	NTUA	NTUA		872.3
Mine Well Field	Peabody	Peabody	[2]4,209.6	
Bacavi	Hopi	USGS/Hopi	22.0	
Hopi Civic Center	Hopi	USGS/Hopi	2.0	
Hopi Cultural Center	Hopi	USGS/Hopi	7.8	
Kykotsmovi	Hopi	USGS/Hopi	70.6	
Mishongnovi	Hopi	USGS/Hopi	7.0	
Moenkopi	Hopi	USGS/Hopi		72.1
Polacca	Hopi	USGS/Hopi	[3]123.3	
Shipaulovi	Hopi	USGS/Hopi	23.9	
Shungopovi	Hopi	USGS/Hopi	28.0	

[1]Well taken out of service.
[2] Industrial pumpage.
[3] Estimated. Well PM4 not metered. Pumpage from PM4 was estimated as 40 acre-feet on the basis of previous metered data and a per capita consumption of 40 gallons per day. Pumping from the remaining wells (PM5 and PM6) may include some water from the D aquifer.

aquifer, characteristics of the wells vary considerably. Construction dates range from 1935 to 1980, depths range from 107 to 3,640 ft, and depths to the top of the N aquifer range from 0 to 2,530 ft (table 6).

From 1998 to 1999, water levels declined in 25 of 31 measured wells. The median water-level decline in the 31 wells was 0.8 ft. Changes ranged from a decline of 18.7 ft in the Kykotsmovi PM1 well to a rise of 8.9 ft in BM observation well 3 (table 5).

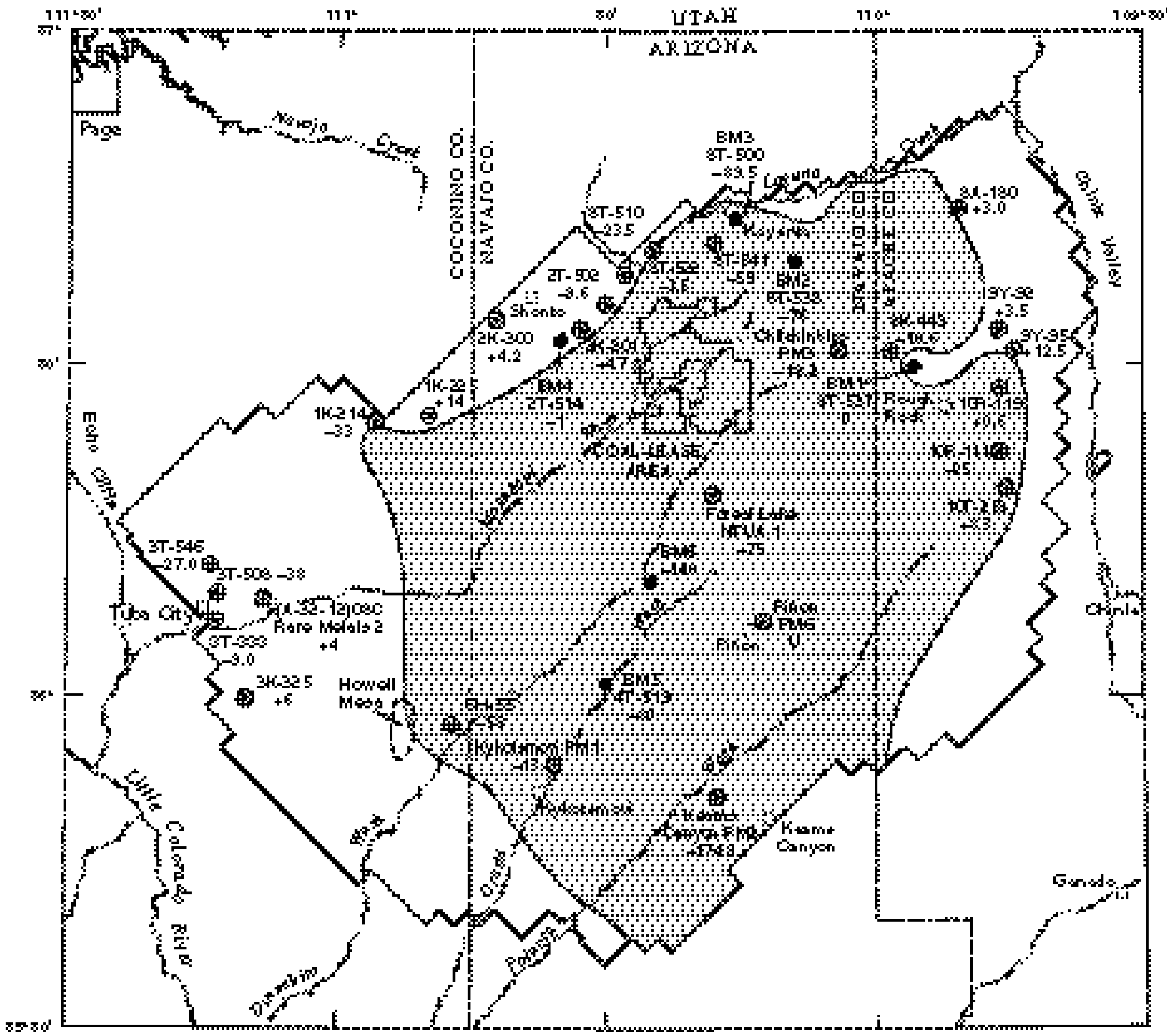
From 1998 to 1999, water levels declined in 11 of 15 wells in unconfined areas. The median decline was 0.7 ft, and the changes ranged from -4.9 ft to +0.3 ft. In confined areas, water levels declined in 14 of 16 wells. The median decline was 1.2 ft, and the changes ranged from -18.7 ft to +8.9 ft (table 5).

The rates of annual water-level changes for observation wells in unconfined and confined areas have not appreciably changed since 1983, and the changes from 1998 to 1999 were less than a 1-foot difference from the average annual median

Table 4. Flowmeter-test results for municipal wells that are completed in the N aquifer, Black Mesa area, Arizona, 1999

Well name	Date tested	Pumping rate, in gallons per minute		Percent difference[2]	Name and number of permanent meter
		Permanent meter	Test meter[1]		
Navajo Tribal Utility Authority (NTUA)					
Chilchinbito 1	05–18–99	48	47	+2.1	Rockwell 1175064
Chilchinbito 2	05–18–99	60	59	+1.7	Rockwell 1236134
Dennehotso 1	05–18–99	71	68	+4.4	Rockwell 3344700
Dennehotso 2	05–18–99	96	97	-1.0	Rockwell 1306471
Forest Lake	05–18–99	55	49	+12.2	Hersey 6049985
Hard Rock 1	06–10–99	118	119	-0.8	Brooks 8405-24272-1-1
Hard Rock 2	([3])	([3])	([3])	([3])	([3])
Kayenta 1	05–25–99	121	123	-1.6	Sensus 1541749
Kayenta 6	01–07–99	148	146	+1.4	Sensus 1412051
Kayenta 7	05–25–99	101	92	+9.8	Sensus 1436356
Kitsillie 1	05–19–99	44	41	+7.3	Sensus 52139870
Kitsillie 2	05–19–99	75	79	-5.1	Sensus 1451526
Piñon 1	05–19–99	95	98	-3.1	Sensus 1442466
Piñon 2	05–19–99	123	119	+3.4	Sensus 1432493
Rough Rock 1	05–19–99	32	32	0	Rockwell 1320677
Rough Rock 2	05–19–99	82	84	-2.4	Sensus 1329324
Bureau of Indian Affairs (BIA)					
Chilchinbito PM3	05–09–99	24	24	0	Precision P521349
Kayenta 2	05–17–99	111	110	+0.9	Neptune 31973644
Kayenta 3	05–26–99	150	153	-2.0	Rockwell 1305841
Piñon PM6	([4])	([4])	([4])	([4])	([4])
Red Lake PM1	05–17–99	47	46	+2.2	Master Meter 1365600
Red Lake PM2	([5])	([5])	([5])	([5])	([5])
Rocky Ridge	06–09–99	52	52	0	Rockwell 1331029
Rough Rock PM3	05–26–99	50	50	0	Rockwell 36880399
Rough Rock PM5	05–26–99	38	38	0	Rockwell 36726380
Rough Rock PM7	([6])	([6])	([6])	([6])	([6])
Shonto PM2	05–17–99	167	169	-1.2	Rockwell 1255896
Shonto PM3	05–17–99	93	91	+2.2	Rockwell 1300477
Shonto PM4	05–17–99	73	72	+1.4	Sensus 1325584

[1]Sensus 125-W portable large meter tester.
[2]A positive difference indicates that the permanent meter is registering more pumpage than the test flowmeter.
[3]Well not in use at date of test (June 10, 1999).
[4]Well not used in 1999.
[5]Well not used since 1995.
[6]Well not tested because test flowmeter could not be connected.



Base from U.S. Geological Survey digital data, 1:100,000, 1980
Lambert Conformal Conic projection
Standard parallels 29°30' and 45°30', central meridian -96°00'

Modified from Brown and Eychaner (1988)

0 25 MILES
0 25 KILOMETERS

EXPLANATION

APPROXIMATE BOUNDARY BETWEEN CONFINED AND UNCONFINED CONDITIONS—From Eychaner (1983)

CONFINED

UNCONFINED

BOUNDARY OF MATHEMATICAL MODEL—From Eychaner (1983)

6H-55 / -58 — WELL IN WHICH DEPTH TO WATER WAS MEASURED ANNUALLY—First entry, 6H-55, is Bureau of Indian Affairs site number; second entry, -58, is change in water level, in feet, between measurement made during the prestress period and measurement made during 1999. U, unable to measure

BM2 / 8T-538 / -76 — CONTINUOUS WATER-LEVEL RECORDING SITE (OBSERVATION WELL) MAINTAINED BY THE U.S. GEOLOGICAL SURVEY—First entry, BM2, is U.S. Geological Survey well number; second entry, 8T-538, is Bureau of Indian Affairs site number; third entry, -76, is change in water level, in feet, from simulated prestress period to 1999

Figure 5. Water-level changes in N-aquifer wells from the prestress period to 1999, Black Mesa area, Arizona. See table 5.

Table 5. Water-level changes in wells completed in the N aquifer, Black Mesa area, Arizona, prestress period to 1999

[Dashes indicate no data. Do., ditto; P, recently pumped; R, reported]

Common name or location	Bureau of Indian Affairs site number	Change in water level from preceding year, in feet		Water level, in feet below land surface, 1999	Prestress period water level[1]		Change in water level from prestress period to 1999, in feet
		1998	1999		Feet below land surface	Date	
Unconfined area							
BM observation well 1[2]	8T-537	-0.3	0.0	374.2	374	([2])	0
BM observation well 4[2]	2T-514	-0.3	-1.0	217.3	[3]216	([2])	-1
Cow Springs	1K-225	+1.2	0.0	45.8	60	07–04–54	+14
Long House Valley	8T-510	-1.5	-0.9	122.9	99.4	08–22–67	-23.5
Northeast Rough Rock	8A-180	-0.1	-0.7	43.9	46.9	11–13–53	+3.0
Rough Rock	9Y-95	+7.8	+0.3	107.0	119.5	08–03–49	+12.5
Do.	9Y-92	+1.4	-0.5	165.3	168.8	12–31–52	+3.5
Shonto	2K-300	[4]+0.3	-0.8	172.3	176.5	06–13–50	+4.2
Shonto Southeast	2K-301	-0.8	-0.4	288.6	283.9	12–10–52	-4.7
Do.	2T-502	+2.6	-0.9	415.4	405.8	08–22–67	-9.6
Tuba City	3T-333	-1.5	-1.2	32.0	23.0	12–02–55	-9.0
Do.	3K-325	+0.5	-0.5	202.0	208	06–30–55	+6
Tuba City Rare Metals 2	---	+0.1	0.0	52.6	57	09–24–55	+4
Tuba NTUA 1	3T-508	[4]-3.4	-4.9	67.2	29	02–12–69	-38
Tuba NTUA 4	3T-546	([5])	-0.8	60.7	33.7	08–06–71	-27.0
Confined area							
BM observation well 2[2]	8T-538	-2.4	-1.3	201.5	125	([2])	-76
BM observation well 3[2]	8T-500	-3.8	+8.9	144.5	[3]55.0	04–29–63	-89.5
BM observation well 5[2]	4T-519	-3.0	-3.3	404.1	324	([2])	-80
BM observation well 6[2]	---	-3.2	-7.4	836.7	[3]697	([2])	-140
Chilchinbito PM3	---	([5])	[4]+0.8	423.5	405.3	09–25–65	-18.2
Forest Lake NTUA 1	4T-523	-5.4	-4.8	1,171.3P	1,096R	05–21–82	-75
Howell Mesa	6H-55	([5])	[4]-1.0	270.2	212	07–08–54	-58
Kayenta West	8T-541	-6.4	-1.6	286.4	227	07–17–79	-59
Keams Canyon PM2	---	[4]-10.1	-4.5	467.3	292.5	06–10–70	-174.8
Kykotsmovi PM1	---	[4]+22.0	-18.7	232.9	220	05–20–67	-13
Marsh Pass[6]	8T-522	-0.5	-0.6	129.0	125.5	02-07-72	-3.5
Piñon PM6	---	-5.0	([5])	([5])	743.6	05–28–70	([5])
Rough Rock	10R-119	0	-0.8	256.0	256.6	12–02–52	+0.6
Do.	10T-258	+5.8	-0.5	309.3	301.0	04–14–60	-8.3
Do.	10R-111	+0.1	-4.0	195.0	170	08–04–54	-25
Sweetwater Mesa	8K-443	[4]-0.9	-0.4	540.0	529.4	09–26–67	-10.6
White Mesa Arch[6]	1K-214	-0.5	-0.3	220.6	188	06–04–53	-33

[1]Prestress refers to the period of record before appreciable ground-water withdrawals for mining or municipal purposes—about 1965. For wells that had no water-level measurement before 1965, the earliest water-level measurement is shown.
[2]Continuous recorder. Except for well BM3, prestress water levels were estimated from the ground-water model by Brown and Eychaner (1988).
[3]Prestress water levels for indicated wells were changed from previous Black Mesa monitoring reports to more accurately represent prestress conditions. BM3 was 77.1 feet in 1998 report and 60 feet in 1995–97 reports. BM4 was 217 feet, and BM 6 was 735.6 feet in 1995–98 reports.
[4]Change in water level from last measurement 2 to 4 years earlier.
[5]Water level not measured because of obstruction in well, no access to well, or not visited.
[6]Classification of well changed from unconfined area in previous Black Mesa monitoring reports to confined area in this report.

Table 6. Well-construction characteristics, top of N aquifer, and type of data collected for study wells, Black Mesa area, Arizona, 1999

Bureau of Indian Affairs site number, or common name	Date well was completed	Land-surface altitude, in feet	Well depth, in feet below land surface	Screened/open interval(s), in feet below land surface	Depth to top of N aquifer, in feet below land surface[1]	Type of data collected in 1999
8T-537 (BM observation well 1)	02–01–72	5,864	850	300–360; 400–420; 500–520; 600–620; 730–780	290	Water level
8T-538 (BM observation well 2)	01–29–72	5,656	1,338	470–1,338	452	Water level
8T-500 (BM observation well 3)	07–29–59	5,724	868	712–868	155	Water level
2T-514 (BM observation well 4)	02–15–72	6,320	400	250–400	160	Water level
4T-519 (BM observation well 5)	02–25–72	5,869	1,683	1,521–1,683	1,520	Water level
BM observation well 6	01–31–77	6,332	2,507	1,954–2,506	1,950	Water level
1K-214	05–26–50	5,771	356	168–356	250	Water level
1K-225	07–04–54	5,722	251	19–251	[2]10	Water level
2K-300	[3]06–00–50	6,264	300	260–300	0	Water level
2K-301	06–12–50	6,435	500	318–328 378–500	[2]30	Water level
2T-502	08–10–59	6,670	523	12–523	[2]5	Water level
3K-325	06–01–55	5,250	450	75–450	[2]30	Water level
3T-333	12–02–55	4,940	229	63–229	[2]4	Water level
3T-508	08–25–99	5,119	475	([4])	0	Water level, withdrawals
3T-546	[3]08–00–71	5,206	612	256–556	0	Water level, withdrawals
4T-523	10–01–80	6,654	2,674	1,870–1,910 2,070–2,210 2,250–2,674	([5])	Water level, water quality, withdrawals
6H-55	12–08–44	5,635	361	310–335	310	Water level
8A-180	01–20–39	5,200	107	60–107	[2]40	Water level
8A-295	[3]00–00–36	5,623	840	268–280 691–788	95	Water quality, withdrawals
8K-443	08–15–57	6,024	720	619–720	590	Water level
8K-521	06–05–64	5,005	675	475–675	[2]5	Water quality, withdrawals
8T-510	02–11–63	6,262	314	130–314	[2]125	Water level
8T-522	[3]07–00–63	6,040	933	180–933	480	Water level
8T-541	03–17–76	5,885	890	740–890	700	Water level
9Y-92	01–02–39	5,615	300	154–300	[2]50	Water level

See footnotes at end of table.

Table 6. Well-construction characteristics, top of N aquifer, and type of data collected for study wells, Black Mesa area, Arizona, 1999—Continued

Bureau of Indian Affairs site number, or common name	Date well was completed	Land-surface altitude, in feet	Well depth, in feet below land surface	Screened/open interval(s), in feet below land surface	Depth to top of N aquifer, in feet below land surface[1]	Type of data collected in 1999
9Y-95	11–05–37	5,633	300	145–300	[2]68	Water level
10R-111	04–11–35	5,757	360	267–360	210	Water level
10R-119	01–09–35	5,775	360	([4])	310	Water level
10T-258	04–12–60	5,903	670	465–670	460	Water level
Chilchinbito PM3	09–25–65	5,950	1,600	1,140–1,570	1,136	Water level, withdrawals
Keams Canyon PM2	[3]05–00–70	5,809	1,106	906–1,106	900	Water level, water quality, withdrawals
Kitsillie NTUA 2	11–09–93	6,780	2,620	2,217–2,223 2,240–2,256 2,314–2,324 2,344–2,394 2,472–2,527	2,205	Water quality, withdrawals
Kykotsmovi PM1	02–20–67	5,657	995	655–675 890–990	880	Water level, withdrawals
Kykotsmovi PM2	10–14–77	5,717	1,160	950–1,160	890	Water quality, withdrawals
Kykotsmovi PM3	08–07–68	5,618	1,220	850–1,220	840	Water quality, withdrawals
Piñon PM6	[3]02–00–70	6,359	2,248	1,895–2,243	1,870	Water level, withdrawals
Peabody 2	[3]06–00–67	6,530	3,640	1,816–3,629	2,530	Water quality, withdrawals
Peabody 4	[3]05–00–68	6,229	3,535	2,029–3,458	2,280	Water quality, withdrawals
Red Lake PM1	[3]09–00–57	5,616	550	150–510	120	Water quality, withdrawals
Rocky Ridge PM2	06–26–63	5,985	1,780	1,480–1,780	1,442	Water level, water quality, withdrawals
Rough Rock PM5	06–27–64	6,299	1,420	1,180–1,420	1,156	Water quality, withdrawals
Tuba City Rare Metals 2	[3]09–00–55	5,108	705	100–705	[2]55	Water level

[1]Depth to top of N aquifer from Eychaner (1983) and Brown and Eychaner (1988).
[2]All material between land surface and top of the N aquifer is unconsolidated—soil, alluvium, or dune sand.
[3]00, indicates month or day is unknown.
[4]Screened and (or) open intervals are unknown.
[5]Top of N aquifer was not estimated.
[6]Water level was not measured in 1999.

changes for 1983–99 (fig. 6). The median change of -0.7 ft from 1998 to 1999 in unconfined areas was a decline, but the average annual median change from 1983 to 1999 was a rise of 0.2 ft. The median decline of 1.2 ft from 1998 to 1999 in confined areas was smaller than the average annual median decline of 1.9 ft.

From the prestress period (prior to 1965) to 1999, the median water-level decline in 31 wells was 10.6 ft. Water levels in 15 unconfined wells had a median change of 0.0 ft and ranged from a 38-foot decline to a 14-foot rise (table 5). Water levels in 16 confined wells had a median decline of 45.5 ft and ranged from a decline of 174.8 ft to a rise of 0.6 ft.

Hydrographs of water levels in wells in the annual observation network show the time trends of changes since about 1970 or 1980 (fig. 7). Water levels have changed only slightly in wells in unconfined areas. In contrast, water levels in wells in confined areas are more variable. In some wells, large declines occurred, and, in other wells, only small changes occurred.

Hydrographs for the Black Mesa observation wells show continuous water-level changes since about 1972 (fig. 8). Water levels in the two wells in unconfined areas (BM1 and BM4) have had small seasonal or year-to-year variation and have had small long-term changes since 1972. Water levels in the four wells in confined areas also have had little seasonal variation (except BM3); however, the water levels have consistently declined in all the confined wells since 1972.

In the mid-1990's, water levels were measured annually in 36 wells. In 1999, only 31 wells were measured; four wells were removed from the monitoring program and one well (Piñon PM6) could not be measured because access was not available. Wells, 3A-28, 3K-311, and Kykotsmovi PM3, have permanent obstructions that prevent measurements. The well, Rocky Ridge PM2, has anomalous water-level data for 1997–2000 that are assumed to be nonrepresentative of water levels in the N aquifer. The water levels for Rocky Ridge PM2 for 1997–2000 are 90 to 200 ft higher than the levels for the previous 10 years (1987–96). From 1996 to 1997, the water level in the well rose

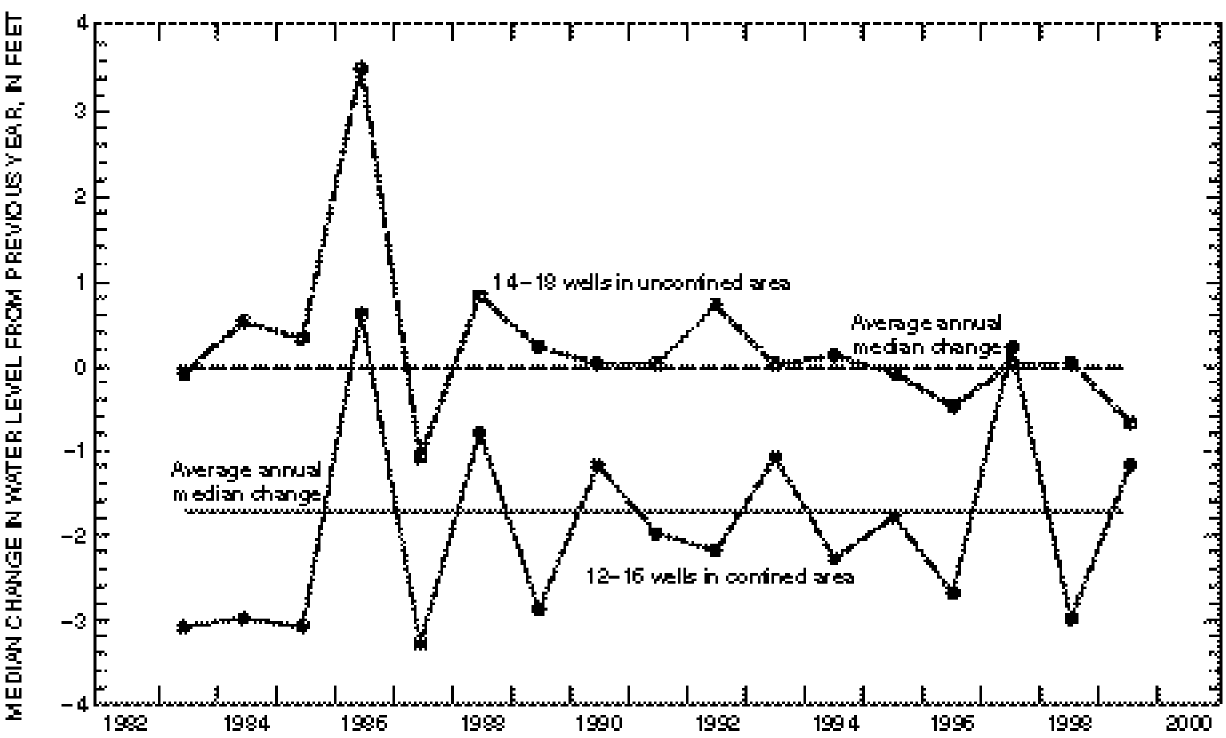


Figure 6. Rates of annual water-level changes for observation wells completed in the N aquifer, Black Mesa area, Arizona, 1983–99.

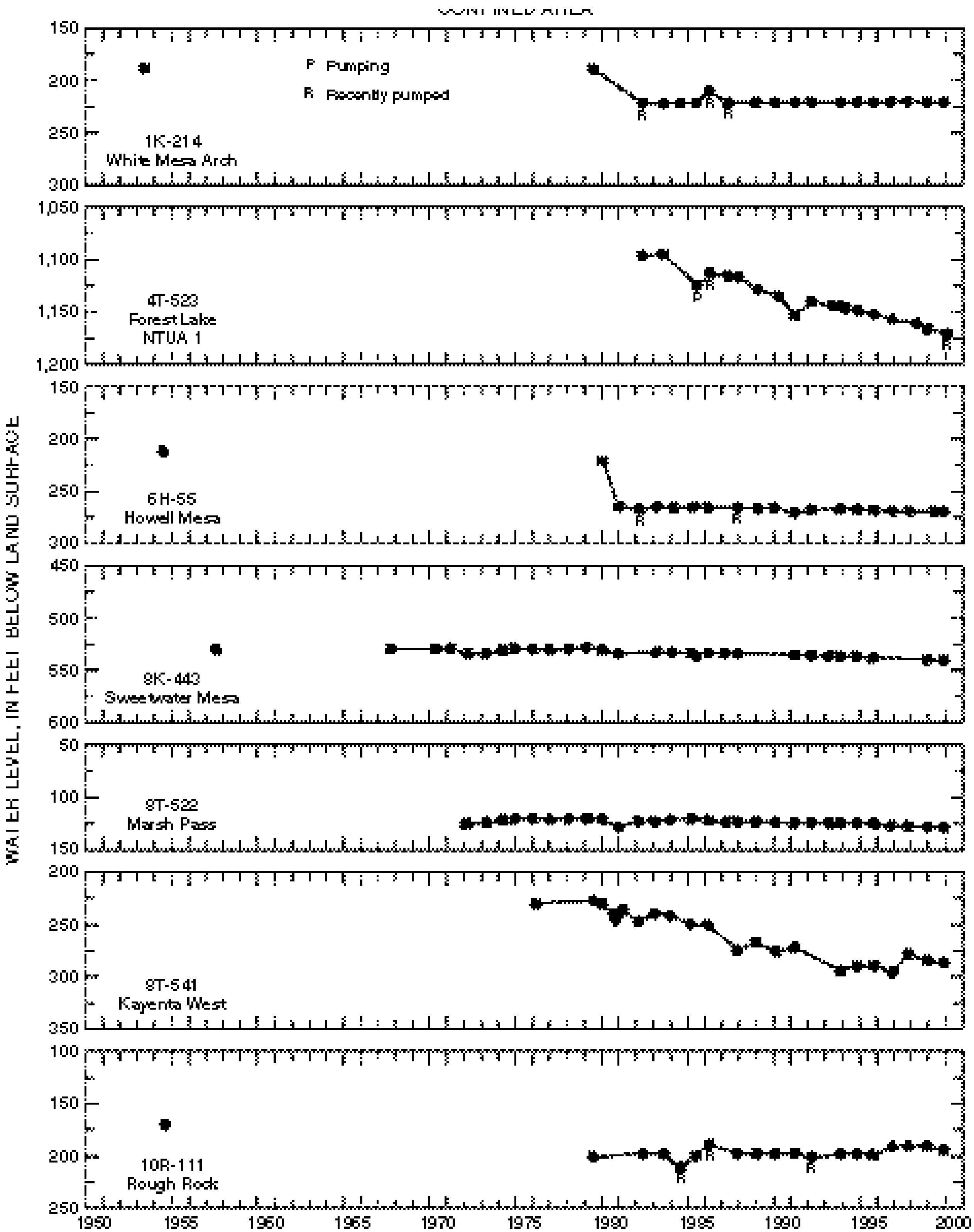


Figure 7. Water-level changes in wells used for annual water-level measurements, Black Mesa area, Arizona, 1950–2000.

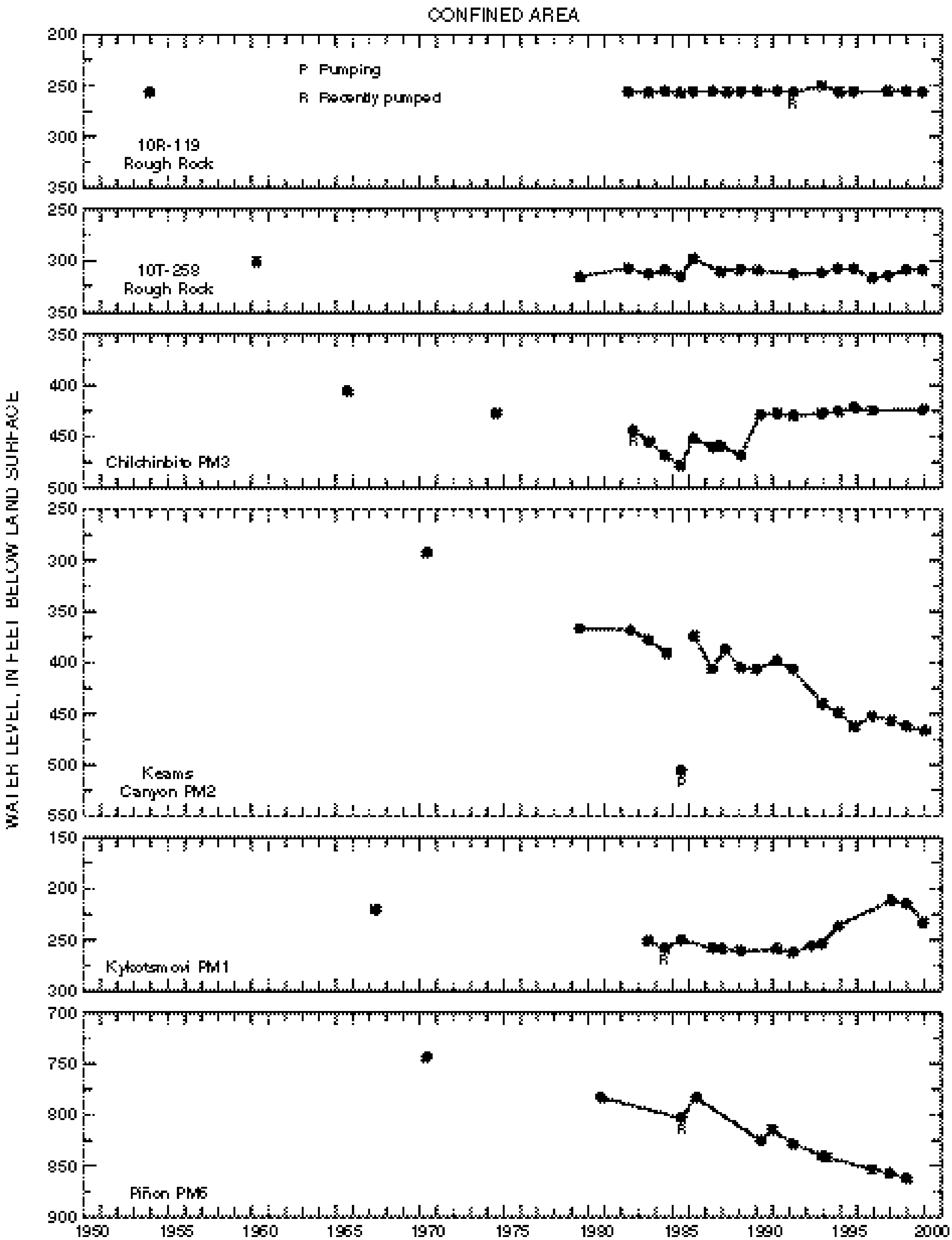


Figure 7. Continued.

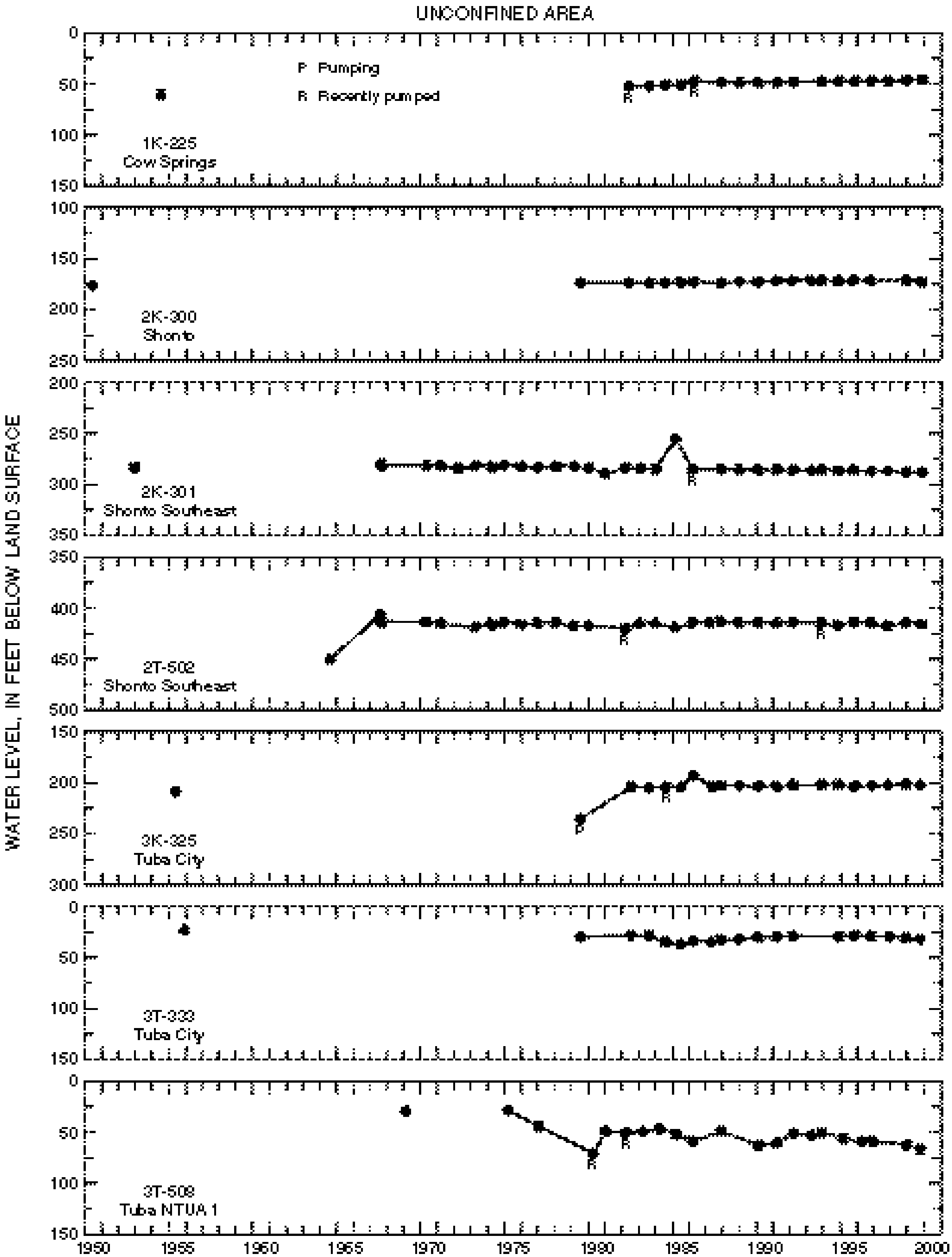


Figure 7. Continued.

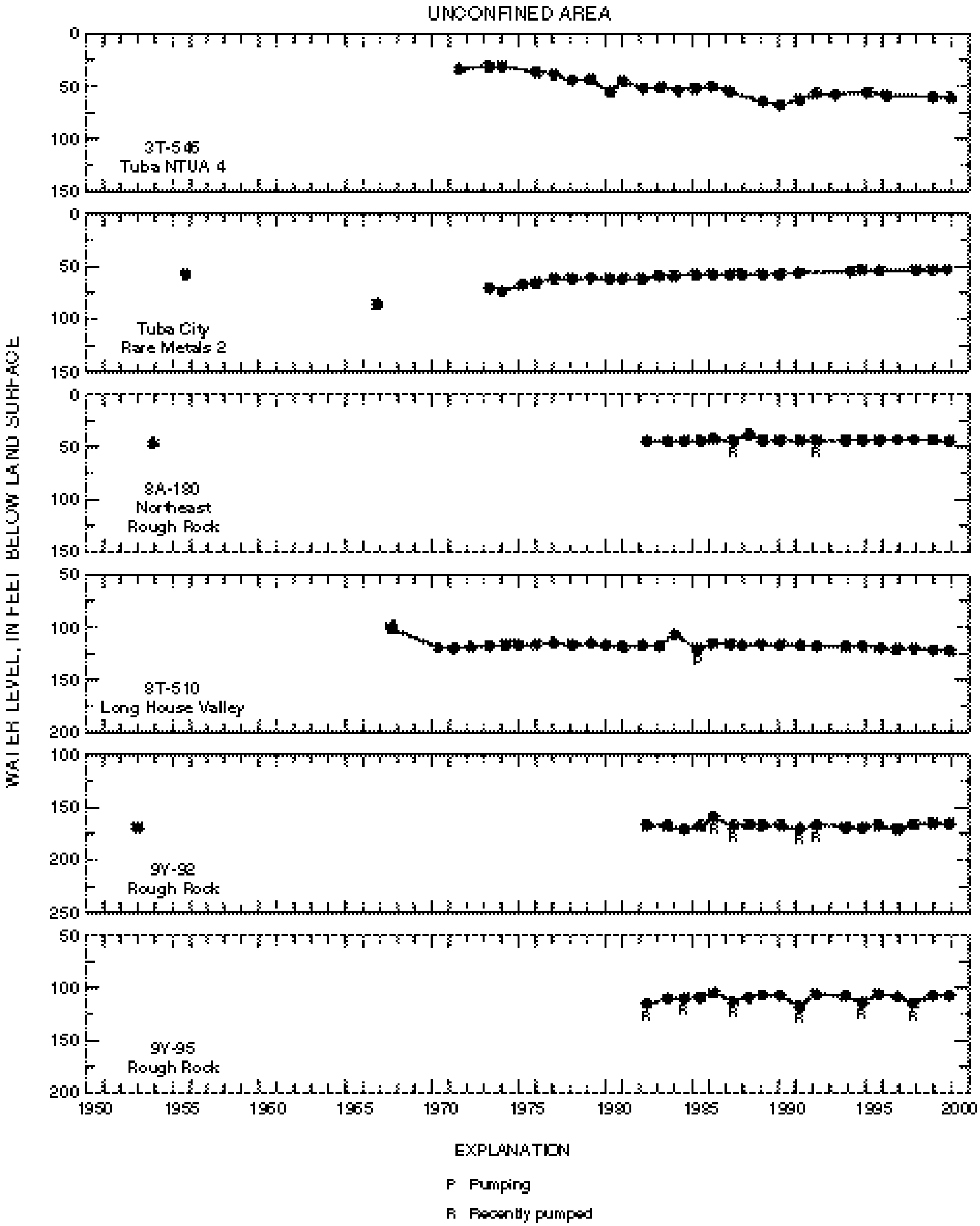


Figure 7. Continued.

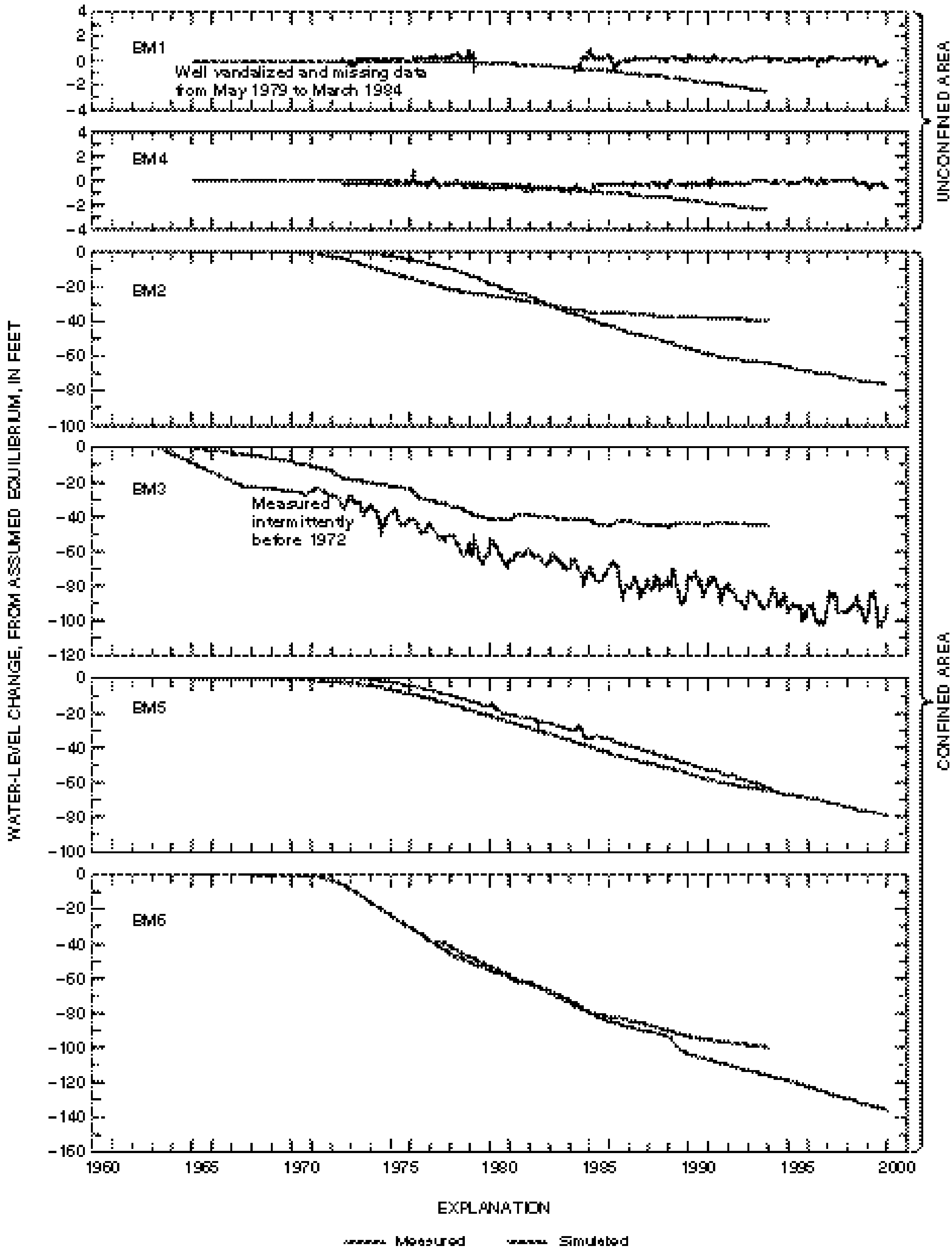


Figure 6. Measured water-level changes in continuous-record observation wells BM1–BM6, 1963–99, and simulated water-level changes, 1965–99, Black Mesa area, Arizona. Simulated data from Littin and Monroe (1995a).

146 ft. That increase is not physically possible in the natural N-aquifer system in Black Mesa. Because there have been no construction changes to the open interval of the well and there is no known physical evidence for the water-level increase, the most likely cause of the increase in water levels is a break in the well casing that would allow water from higher formations to enter the well.

The 31 observation wells are classified as being in confined or unconfined areas of the N aquifer (table 5, fig. 5). After a review of data, this classification was changed for two wells since the last Black Mesa monitoring report (Truini and others, 2000). Wells 1K-214 (White Mesa Arch) and 8T-522 (Marsh Pass) were changed from unconfined to confined. This reclassification is not entirely certain, but most evidence points toward confined conditions. Water levels in these wells are above the top of the N aquifer and the aquifer is overlain by a confining bed, which is the definition of confined conditions. The open intervals, however, extend from the N aquifer to above the aquifer; therefore, there is uncertainty about the effect of water from overlying formations on the measured water levels. Because most of the open intervals are in the N aquifer, the assumption is that the measured water levels are largely controlled by water from the N aquifer.

Spring Discharge from the N Aquifer

Ground water in the N aquifer discharges from many springs around the margins of the Black Mesa area. Discharge from selected springs is measured annually and compared to discharge from previous years to determine changes in spring discharge over time. In December 1999, discharge was measured at four springs (table 7). Three springs are on the west or southwest side of the Black Mesa area, and one is on the northeast side (fig. 9). The discharge from these four springs represents only a small fraction of the total spring discharge from the N aquifer.

In 1999, measured discharges were 0.3 gal/min from Burro Spring, 14.8 gal/min from an unnamed spring near Dennehotso, 13.3 gal/min from Moenkopi School Spring, and 38 gal/min from Pasture Canyon Spring. Compared to spring discharges in 1998, discharges did not change for Burro Spring, decreased by 30 percent for an unnamed spring near Dennehotso, increased by 11 percent for Moenkopi School Spring, and decreased by 3 percent for Pasture Canyon Spring. The discharges measured at all four springs represent only part of the total discharges from the springs. Because of separate seeps and problematic measuring conditions, it would be difficult to measure the total discharge at those sites.

Long-term changes in spring discharge can be evaluated for the entire record at Burro Spring but can be evaluated only for parts of the records for the other three springs because discharge measuring points changed during the periods of record. Consistent measuring points are available for 1992–99 at an unnamed spring near Dennehotso, for 1987–99 at Moenkopi School Spring, and for 1995–99 at Pasture Canyon Spring. For the consistent periods of record at all four springs, the discharges have fluctuated; however, increasing or decreasing trends are not apparent.

Surface-Water Discharge

Surface-water discharge in the study area includes ground-water discharge and direct or shallow subsurface runoff of rainfall or snowmelt. Ground-water discharges to surface water at a fairly constant rate throughout the year. In contrast, the amount of rainfall or snowmelt runoff varies widely throughout the year. In the winter and spring, the amount and timing of snowmelt runoff is a result of the temporal variation in snow accumulation, air temperatures, and rate of snowmelt. Although most rainfall runoff is in the summer, rainfall can cause surface-water discharge any time of the year. The amount and timing of rainfall runoff is a result of the intensity and duration of thunderstorms in the summer and cyclonic storms in the fall, winter, and spring.

Data on surface-water discharge have been collected continuously at selected streams each year of the monitoring program. The discharge data provide useful information about ground-water discharge and about runoff from rainfall and snowmelt. In this study, the total discharge in streams is roughly separated into

Table 7. Discharge measurements of selected springs, Black Mesa area, Arizona, 1952–99

U.S. Bureau of Indian Affairs site number	Rock formation(s)	Date of measurement	Discharge, in gallons per minute
Burro Spring			
6M-31	Navajo Sandstone	12–15–89	0.4
		12–13–90	0.4
		03–18–93	0.3
		12–08–94	0.2
		12–17–96	0.4
		12–30–97	0.2
		12–08–98	0.3
		12-07-99	0.3
Unnamed spring near Dennehotso			
8A-224	Navajo Sandstone	10–06–54	[3]1
		06–27–84	[3]2
		11–17–87	[3]5
		03–26–92	16
		10–22–93	14.4
		12–05–95	17
		12–19–96	15.7
		12–31–97	25.6
		12–14–98	21.0
		12–15–99	14.8

U.S. Bureau of Indian Affairs site number	Rock formation(s)	Date of measurement	Discharge, in gallons per minute
Moenkopi School Spring			
3GS-77-6	Navajo Sandstone[1]	05–16–52	40
		04–22–87	[2]16
		11–29–88	[2]12.5
		02–21–91	[2]13.5
		04–07–93	[2]14.6
		12–07–94	[2]12.9
		12–04–95	[2]12.1
		12–16–96	[2]10
		12–17–97	[2]13.1
		12–08–98	[2]12.0
		12-13-99	[2]13.3
Pasture Canyon Spring			
3A-5	Navajo Sandstone, alluvium	11–18–88	[4]211
		03–24–92	[4]233
		10–12–93	[4]211
		12–04–95	[5]38
		12–16–96	[5]38
		12–17–97	[5]40
		12–10–98	[5]39
		12–21–99	[5]38

[1]Tongue in the Kayenta Formation.
[2]Discharge measured at water-quality sampling site and at different point than the measurement in 1952. Discharge does not represent total discharge from the Moenkopi School Spring system.
[3]Discharge measured at different point than later measurements and does not represent total discharge from unnamed spring near Dennehotso.
[4]Discharge measured in an irrigation ditch about 0.25 mile below water-quality sampling point and does not represent total discharge from Pasture Canyon Spring.
[5]Discharge measured at water-quality sampling point 20 feet below uppermost spring. Discharge does not represent total discharge from Pasture Canyon Spring.

ground-water discharge and runoff so that the temporal trends in ground-water discharge can be monitored.

In 1999, continuous-record discharge data were collected at four streamflow-gaging stations (tables 8–11). The gaging stations are in four of the largest drainages of the study area—Moenkopi Wash, Laguna Creek, Dinnebito Wash, and Polacca Wash (fig. 9, table 12).

The annual average discharges for the four gaging stations vary considerably during their periods of record; therefore, it is difficult to discern any trends (fig. 10). The discharges in Moenkopi Wash appear to have become more variable during the last 10 years.

The ground-water discharge component of total flow at the four streamflow-gaging stations was roughly estimated by computing the median flow for four winter months—November, December, January, and February. Most flow during the winter is ground-water discharge because rainfall and snowmelt runoff are minimal. Most of the precipitation in the winter falls as snow, and the cold temperatures prevent appreciable snowmelt. Also, evapotranspiration from streams is at a minimum during the winter. During the summer, much of the flow in streams evaporates or is transpired by plants. The median flow for November, December, January, and February, rather than the average flow, is used to estimate ground-water discharge because the median is less affected by occasional winter runoff. The 120 consecutive daily mean flows for those four months were used to compute the median flow. These winter flows are a part of a water year—October 1 to September 30.

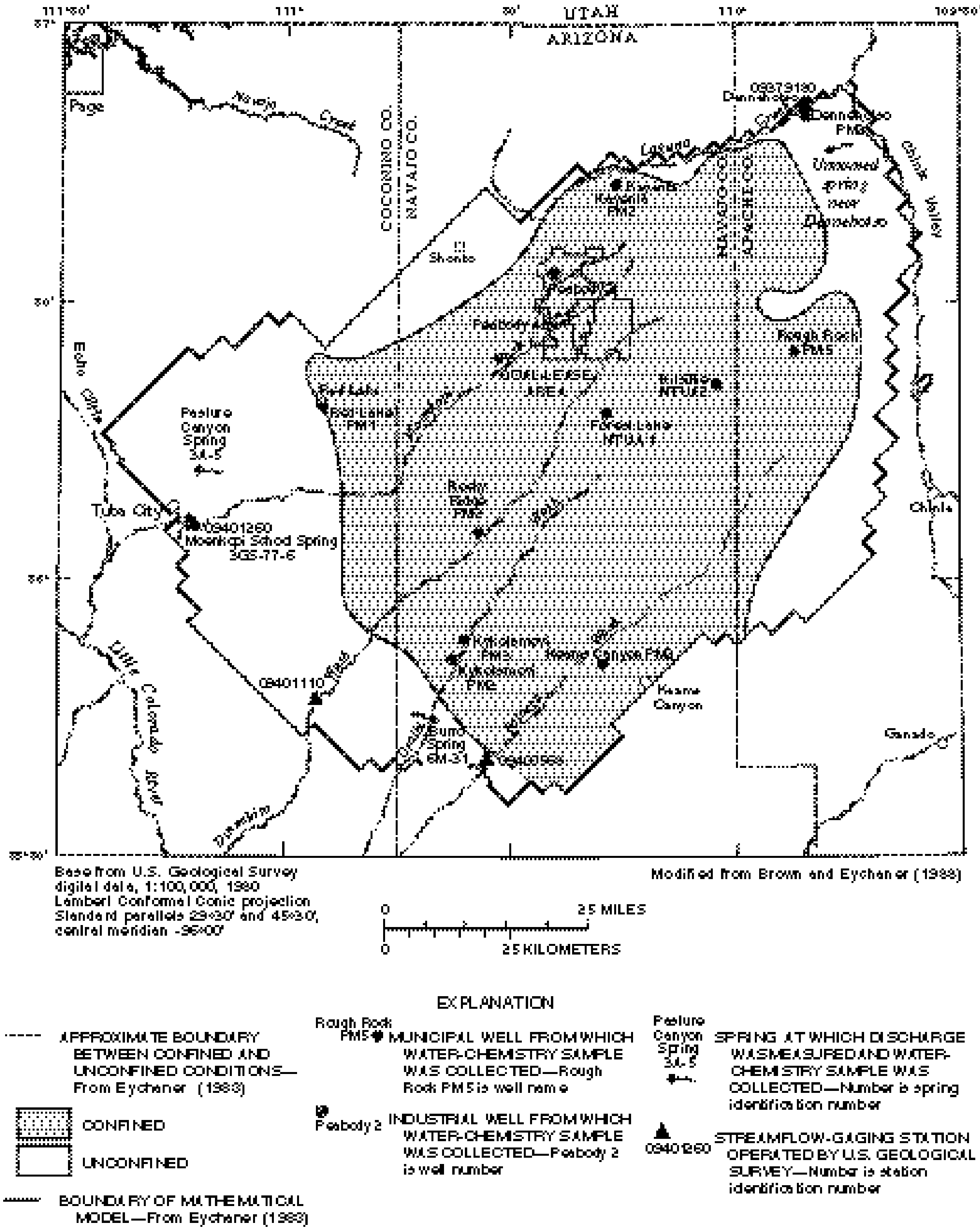


Figure 9. Surface-water and water-chemistry data-collection sites, Black Mesa area, Arizona, 1999.

Table 8. Discharge data, Moenkopi Wash at Moenkopi, Arizona (09401260), calendar year 1999

[Dashes indicate no data]

DISCHARGE, IN CUBIC FEET PER SECOND, CALENDAR YEAR 1999 DAILY MEAN VALUES												
Day	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.[1]	Nov.[1]	Dec.[1]
1	4.2	[2]3.7	2.5	3.2	3.1	[2]0.30	0.0	13	1,200	1.2	1.7	1.7
2	2.6	[2]2.7	2.6	3.3	3.0	[2]2.0	.0	[2]30	156	1.1	1.8	2.1
3	2.1	[2]2.7	2.6	3.6	3.3	14	.0	6.8	44	1.1	1.8	2.6
4	1.7	[2]2.7	2.4	3.4	14	2.7	.0	69	17	1.1	2.0	3.0
5	2.7	3.5	2.4	3.6	7.6	.83	.0	29	9.5	1.1	2.0	2.3
6	2.9	3.2	2.3	3.5	1.5	.97	.0	[2]10	5.3	[2].99	2.0	1.3
7	3.5	3.1	2.4	3.0	1.6	.63	.22	[2]10	3.1	.83	2.0	4.2
8	3.3	3.2	2.5	2.4	1.1	.14	4.1	[2]5.0	2.2	.83	2.2	3.5
9	3.0	3.1	2.4	3.2	[2].50	.01	4.4	[2]4.0	1.5	.82	2.2	3.3
10	3.2	3.3	2.3	3.1	.23	.0	5.0	[2]3.0	.94	1.0	2.1	5.5
11	3.2	2.9	2.4	3.2	.23	.03	4.9	[2]3.0	22	1.1	1.8	8.9
12	4.0	2.4	2.5	2.9	.17	.03	4.8	[2]3.0	88	1.1	1.8	3.5
13	[2]3.7	2.8	2.3	3.9	.22	.0	[2]4.0	[2]3.0	14	.95	1.8	7.1
14	[2]2.7	[2]2.7	2.2	3.4	.09	.0	[2]4.0	[2]3.0	8.2	.83	1.8	5.4
15	[2]2.7	3.0	2.4	3.1	.37	.0	[2].90	[2]3.0	6.7	.82	1.8	3.8
16	[2]3.7	[2]2.2	2.6	2.8	1.3	.0	3.8	[2]7.0	8.7	.76	1.9	4.8
17	[2]3.7	2.5	3.2	3.1	1.8	.0	[2]1.0	[2]7.0	38	.66	1.9	3.9
18	3.3	2.5	3.2	3.3	1.8	.0	[2].50	[2]4.4	9.7	.86	1.8	4.1
19	3.1	[2]2.2	3.0	3.0	2.0	.0	[2].50	120	[2]4.0	1.1	1.8	4.4
20	3.2	2.6	2.8	2.6	[2]4.0	.0	.55	860	[2]2.0	1.2	1.8	5.0
21	3.2	2.4	2.7	3.3	8.8	.0	.19	65	[2]1.5	1.1	[2].2	5.0
22	[2]3.0	2.3	2.7	3.5	5.2	.0	[2].20	23	1.4	1.4	2.1	5.4
23	[2]3.0	2.7	2.8	4.2	.77	.0	[2]2.0	[2]10	10	1.4	2.2	5.5
24	3.3	2.5	2.8	3.9	.82	.0	21	[2]10	29	1.6	3.0	5.2
25	2.8	2.5	2.9	3.4	.64	.0	11	[2]10	7.1	1.5	4.4	5.5
26	3.1	2.5	2.9	3.2	.66	.0	1.2	21	[2]1.8	1.5	3.6	7.2
27	[2]3.2	2.6	2.9	3.0	1.6	.0	[2].70	56	[2]1.0	1.5	4.3	6.0
28	[2]3.7	2.7	2.8	2.8	2.4	.0	674	1,050	.80	1.1	2.2	6.7
29	3.3	---	2.7	2.9	[2]2.0	.0	100	917	.81	1.2	2.3	7.3
30	4.2	---	2.8	3.4	[2].60	.0	14	301	1.1	1.4	2.9	6.5
31	3.9	---	2.8	---	[2].40	---	2.2	48	---	1.5	---	8.6
TOTAL	99.2	77.2	81.8	97.2	71.80	21.64	954.26	3,704.2	1,695.35	34.65	67.2	149.3
MEAN	3.2	2.8	2.6	3.2	2.3	.72	31	120	56	1.1	2.2	4.8
MAX	4.2	3.7	3.2	4.2	14	14	674	1,050	1,200	1.6	4.4	8.9
MIN	1.7	2.2	2.2	2.4	.09	.0	.0	3.0	.80	.66	1.7	1.3
AC-FT	197	153	162	193	142	43	1,890	7,350	3,360	69	133	296

CALENDAR YEAR 1999 TOTAL 7,053.8 MEAN 19.3 MAXIMUM 1,200 MINIMUM 0.0 ACRE-FT 13,991

[1]Month in which data are provisional, subject to revision.

[2]Estimated.

Table 9. Discharge data, Laguna Creek at Dennehotso, Arizona (09379180), calendar year 1999

[Dashes indicate no data]

DISCHARGE, IN CUBIC FEET PER SECOND, CALENDAR YEAR 1999 DAILY MEAN VALUES												
Day	**Jan.**	**Feb.**	**Mar.**	**Apr.**	**May**	**June**	**July**	**Aug.**	**Sept.**	**Oct.[1]**	**Nov.[1]**	**Dec.[1]**
1	[2]1.7	[2]0.40	1.4	2.8	0.18	0.0	0.0	6.4	7.1	0.24	1.7	2.3
2	[2]2.9	[2].70	.95	.79	.14	.0	.0	4.6	10	.03	1.8	2.1
3	[2]5.5	[2]3.8	.82	3.7	.17	.0	.0	17	4.3	.55	1.8	2.0
4	[2]4.4	[2]3.2	.67	11	.20	.0	.0	54	2.3	.27	1.8	1.1
5	[2]3.4	[2]3.8	.48	25	.15	.0	.0	62	.95	.09	1.9	.66
6	[2]3.2	[2]3.8	.45	13	1.7	.0	.0	11	.48	.0	1.9	.22
7	[2]3.7	[2]2.9	.40	5.8	.16	.0	.0	5.8	.19	1.1	[2]1.7	.49
8	[2]1.9	6.2	.38	2.4	.13	.0	.08	2.2	.07	.45	[2]1.7	.54
9	[2]1.6	4.5	.38	1.6	.04	.0	14	3.5	.30	.58	[2]1.5	.11
10	[2]3.5	5.0	2.2	.65	.0	.0	87	1.8	.04	.50	[2]1.7	.93
11	[2]3.8	2.8	1.5	.46	.0	.0	9.1	5.9	66	.41	[2]1.7	.58
12	[2]3.6	[2].80	.52	.47	.0	.0	2.3	2.7	53	.75	[2]1.8	2.6
13	[2]2.5	[2].60	.57	.50	.0	.0	.81	1.6	11	.84	[2]1.8	2.6
14	[2]2.9	[2].50	1.0	.53	.0	.0	.39	.93	10	.27	[2]1.9	3.6
15	[2]3.6	[2]1.4	1.5	.80	.0	.0	38	1.0	4.1	.07	[2]1.9	.45
16	7.7	[2]3.8	1.6	.50	.0	.0	28	47	7.3	1.3	[2]2.0	.88
17	6.6	[2]4.4	1.1	.48	.0	.0	4.5	7.3	9.4	1.3	[2]2.0	.65
18	[2]2.5	[2]2.8	.89	.51	.0	19	1.6	11	10	.65	1.6	2.0
19	[2]4.9	[2]2.2	.51	.58	.0	13	.73	115	5.2	.71	1.4	.70
20	[2]8.5	[2]2.4	1.5	.35	.0	1.5	.06	122	2.2	1.2	1.6	1.4
21	7.9	2.1	1.1	.18	.0	.03	.06	22	1.1	.90	2.1	2.0
22	4.8	1.7	.51	.26	.0	.0	1.9	6.8	.09	.58	2.1	3.9
23	[2]2.3	2.0	.34	1.1	.0	.0	1.5	3.0	.0	.36	1.6	2.4
24	[2]2.5	.95	.25	13	.0	.0	.03	2.0	4.0	1.8	.51	2.0
25	[2]3.3	1.1	.23	7.3	.0	.0	.0	29	8.3	1.6	.47	.83
26	6.7	4.0	1.0	1.6	.0	.0	.0	25	3.4	1.3	.82	.29
27	4.4	5.2	.52	.62	.0	.0	.0	14	1.7	1.2	.97	.75
28	3.4	3.2	.55	.31	.0	.0	563	22	.70	1.4	4.4	6.6
29	[2]1.6	---	.55	.27	.0	.0	134	10	.32	1.6	3.3	3.2
30	[2]0.50	---	.54	.15	.0	.0	23	3.2	.33	1.5	2.2	4.0
31	[2].40	---	1.8	---	.0	---	13	4.7	---	1.5	---	1.2
TOTAL	116.20	76.25	26.21	96.71	2.87	33.53	923.06	624.43	223.87	23.05	53.67	53.08
MEAN	3.8	2.7	.85	3.2	.09	1.1	30	20	7.5	.81	1.8	1.7
MAX	8.5	6.2	2.2	25	1.7	19	563	122	66	1.8	4.4	6.6
MIN	.40	.40	.23	.15	.0	.0	.0	.93	.0	.0	.47	.11
AC-FT	230	151	52	192	5.7	67	1,830	1,240	444	50	106	105

CALENDAR YEAR 1999 TOTAL 2,252.93 MEAN 6.2 MAXIMUM 563 MINIMUM 0.0 ACRE-FT 4,469

[1]Month in which data are provisional, subject to revision.
[2]Estimated.

Table 10. Discharge data, Dinnebito Wash near Sand Springs, Arizona (09401110), calendar year 1999

[Dashes indicate no data]

DISCHARGE, IN CUBIC FEET PER SECOND, CALENDAR YEAR 1999 DAILY MEAN VALUES												
Day	**Jan.**	**Feb.**	**Mar.**	**Apr.**	**May**	**June**	**July**	**Aug.**	**Sept.**	**Oct.**[1]	**Nov.**[1]	**Dec.**[1]
1	0.48	0.46	0.42	0.54	0.48	0.25	[2]0.20	[2]10	[2]340	0.37	0.38	0.31
2	.41	.44	.42	.73	.44	.30	[2].20	[2]1.1	[2]45	.35	.38	.30
3	.42	.48	.40	.50	.43	.30	[2].20	[2]7.3	[2]1.2	.34	.39	.28
4	.38	.48	.37	.52	.74	.22	[22].20	[2]20	[2].40	.34	.41	.30
5	.42	.49	.38	.49	.47	.30	[2].20	[2]0.48	[2].39	.34	.40	.29
6	.45	.47	.41	.42	.47	.29	[2].20	[2].13	[2].39	.29	.40	.31
7	.45	.46	.38	.39	.48	.23	.36	[2].13	[2].34	.29	.40	.33
8	.43	.46	.39	.42	.44	.20	[2]5.8	[2].13	.33	.34	.40	.34
9	.41	.43	.41	.38	.39	.21	[2]15	[2].13	.32	.33	.30	.30
10	.43	.50	.42	.44	.41	.20	[2]130	[2].13	.32	.34	.28	.33
11	.46	.39	.41	.45	.43	.21	[2]5.4	[2].13	102	.34	.28	.30
12	.26	.44	.40	.41	.44	.22	[2]4.4	[2].13	23	.34	.28	.28
13	.44	.47	.41	.43	.37	.21	[2]1.2	[2].13	2.5	.34	.28	.31
14	.45	.47	.44	.40	.33	.20	[2]2.6	[2].13	2.0	.35	.29	.31
15	.41	.48	.41	.40	.34	.19	[2]79	[2].13	.83	.33	.26	.19
16	.48	.44	.42	.43	.37	.19	[2]14	[2].13	.36	.31	.26	.22
17	.47	.47	.46	.47	.40	.22	2.7	[2]5.6	78	.32	.28	.41
18	.49	.46	.44	.47	.42	[2]23	.64	[2]30	5.6	.35	.28	.35
19	.49	.45	.43	.47	.39	[2].20	.31	[2]79	1.5	.36	.31	.33
20	.48	.44	.41	.45	.37	[2].20	.25	[2]42	.80	.36	.30	.30
21	.49	.42	.42	.43	.38	[2].20	.24	[2]12	.44	.37	.30	.30
22	.43	.39	.44	.45	.33	[2].20	.59	[2]1.7	.38	.38	.29	.29
23	.46	.42	.43	.57	.30	[2].20	[2]15	[2].76	.76	.38	1.6	.29
24	.50	.46	.45	.44	.32	[2].20	[2]6.7	[2]1.5	1.0	.37	.34	.30
25	.45	.42	.46	.56	.39	[2].20	[2]1.3	[2].56	2.8	.38	.31	.33
26	.46	.42	.42	.47	.40	[2].20	[2]1.2	[2]61	1.0	.37	.33	.35
27	.46	.44	.38	.44	.36	[2].20	[2].31	[2]24	.38	.36	.36	.32
28	.43	.45	.37	.41	.32	[2].20	[2]24	[2]160	.33	.36	.35	.32
29	.41	---	.39	.43	.27	[2].20	[2]56	[2]160	.36	.34	.34	.32
30	.41	---	.40	.47	.25	[2].20	[2]41	[2]120	.38	.35	.33	.32
31	.46	---	.34	---	.25	---	[2]19	[2]67	---	.38	---	.33
TOTAL	13.67	12.60	12.73	13.88	12.18	29.34	428.20	805.43	613.11	10.77	11.11	9.56
MEAN	.44	.45	.41	.46	.39	.98	14	26	20	.35	.37	.31
MAX	.50	.50	.46	.73	.74	23	130	160	340	.38	1.6	.41
MIN	.26	.39	.34	.38	.25	.19	.20	.13	.32	.29	.26	.19
AC-FT	27	25	25	28	24	58	849	1,600	1,220	21	22	19

CALENDAR YEAR 1999 TOTAL 1,972.58 MEAN 5.4 MAXIMUM 340 MINIMUM 0.13 ACRE-FT 3,913

[1]Month in which data are provisional, subject to revision.
[2]Estimated.

Table 11. Discharge data, Polacca Wash near Second Mesa, Arizona (09400568), calendar year 1999

[Dashes indicate no data]

DISCHARGE, IN CUBIC FEET PER SECOND, CALENDAR YEAR 1999
DAILY MEAN VALUES

Day	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.[1]	Nov.[1]	Dec.[1]
1	0.21	0.25	0.26	0.82	0.23	0.09	0.07	0.49	26	0.11	0.14	0.15
2	.20	.25	.26	.95	.22	.10	.08	8.2	4.5	.11	.75	.14
3	.20	.26	.25	.45	.22	.11	.17	8.1	0.44	.11	.19	.15
4	.21	.25	.23	.37	.28	.09	.09	4.4	.06	.11	.16	.14
5	.23	.25	.25	.33	.21	.10	.08	67	.06	.11	.01	.14
6	.25	.23	.25	.26	.21	.10	.08	32	.06	.10	.0	.15
7	.25	.24	.24	.24	.21	.09	.07	1.9	.05	.10	.0	.17
8	.23	.24	.24	.25	.20	.08	.05	.14	.05	.11	.0	.15
9	.23	.23	.25	.26	.17	.08	.05	.07	.05	.12	.06	.11
10	.25	.24	.24	.29	.16	.08	.21	.06	.05	.12	.13	.15
11	.26	.24	.25	.25	.17	.08	.11	.05	20	.11	.13	.16
12	.22	.32	.24	.22	.17	.08	.06	.04	1.5	.12	.13	.12
13	.22	.32	.25	.24	.16	.09	.06	.04	33	.11	.13	.15
14	.23	.31	.25	.22	.14	.08	.90	.04	22	.11	.13	.11
15	.26	.25	.25	.22	.14	.07	1.9	.06	4.1	.11	.14	.08
16	.24	.25	.26	.22	.14	.07	.12	.05	.26	.10	.14	.09
17	.23	.25	.38	.23	.15	.08	.07	.05	34	.10	.14	.12
18	.23	.25	.29	.23	.15	.14	.07	.06	4.6	.12	.13	.12
19	.22	.25	.28	.23	.14	.08	.08	14	15	.12	.14	.13
20	.22	.25	.25	.23	.14	.07	.07	130	4.8	.13	.14	.12
21	.25	.24	.23	.22	.14	.07	.07	73	.26	.13	.14	.11
22	.22	.23	.23	.22	.13	.06	.07	12	.12	.13	.13	.11
23	.25	.26	.23	.22	.12	.06	.08	4.1	17	.13	.12	.10
24	.23	.26	.24	.22	.12	.06	.08	1.5	88	.14	.12	.12
25	.22	.25	.24	.25	.14	.07	.07	.21	15	.13	.13	.12
26	.23	.25	.25	.23	.15	.06	13	4.4	1.5	.13	.16	.14
27	.22	.25	.24	.22	.14	.06	18	23	.17	.13	.16	.15
28	.23	.25	.23	.21	.13	.07	4.4	139	.10	.13	.15	.14
29	.24	---	.23	.20	.11	.07	1.4	143	.11	.12	.15	.15
30	.26	---	.23	.21	.10	.07	11	214	.11	.12	.15	.13
31	.30	---	.22	---	.10	---	1.2	87	---	.13	---	.14
TOTAL	7.24	7.12	7.74	8.71	4.99	2.41	53.76	967.95	292.95	3.65	4.20	4.06
MEAN	.23	.25	.25	.29	.16	.08	1.7	31	9.8	.12	.14	.13
MAX	.30	.32	.38	.95	.28	.14	18	214	88	.14	.75	.17
MIN	.20	.23	.22	.20	.10	.06	.05	.04	.05	.10	.0	.08
AC-FT	14	14	15	17	9.9	4.8	107	1,920	581	7.2	8.3	8.1

CALENDAR YEAR 1999 TOTAL 1,364.78 MEAN 3.7 MAXIMUM 214 MINIMUM 0.0 ACRE-FT 2,707

[1]Month in which data are provisional, subject to revision.

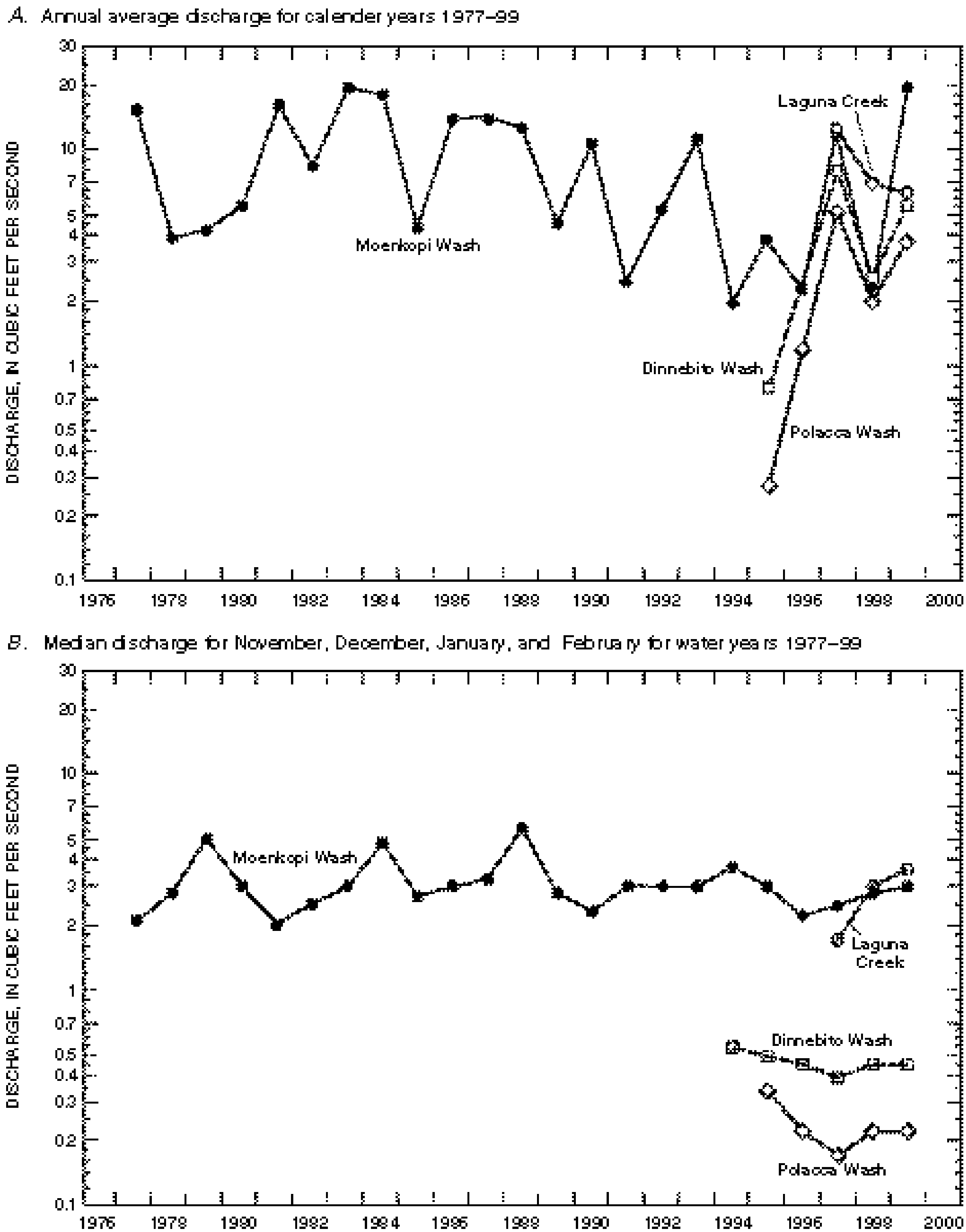


Figure 10. Annual average discharge and median winter discharge, Moenkopi Wash (*09401260*), Laguna Creek (*09379180*), Dinnebito Wash (*09401110*), and Polacca Wash (*09400568*), Black Mesa area, Arizona. *A*, Annual average discharge for calender years 1977–99. *B*, Median discharge for November, December, January, and February for water years 1977–99.

Table 12. Date that data collection began and drainage areas for streamflow-gaging stations, Black Mesa area, Arizona

Station name	Station number	Date data collection began	Drainage area, in square miles
Moenkopi Wash at Moenkopi	09401260	July 1976	1,629
Laguna Creek at Dennehotso	09379180	July 1996	414
Dinnebito Wash near Sand Springs	09401110	June 1993	473
Polacca Wash near Second Mesa	09400568	April 1994	905

The median flow for November, December, January, and February is an index of ground-water discharge rather than an absolute estimate of discharge. A more rigorous and accurate estimate would include detailed evaluations of streamflow hydrographs, flows into and out of bank storage, gain and loss of streamflow as it moves down the stream channel, and interaction of ground water in the N aquifer with ground water in the shallow alluvial aquifers in the stream valleys. The median winter flow, however, is useful as a consistent index for evaluating time trends in ground-water discharge.

The median discharges for November, December, January, and February for the four gaging stations have much less year-to-year variability than the annual average discharges (fig. 10). This difference in variability is expected because the median flows are mostly ground-water discharge, which varies a small amount each year, and the annual average discharges are mostly controlled by precipitation, which varies considerably each year.

In water year 1999, median flows for November, December, January, and February were 3.0 ft^3/s for Moenkopi Wash, 3.6 ft^3/s for Laguna Creek, 0.45 ft^3/s for Dinnebito Wash, and 0.22 ft^3/s for Polacca Wash. Increasing or decreasing trends are not apparent in the median flows for all four gaging stations for the periods of record (fig. 10).

Water Chemistry

Water samples are collected from selected wells and springs each year of the Black Mesa monitoring program. Field measurements are made and water samples are analyzed for major ions, nutrients, iron, boron, and arsenic. During the past 10 years, water samples have been collected from about 30 wells and 10 springs. Each year of the program, samples are collected from about 12 wells and 4 springs. Long-term data for specific conductance, dissolved solids, chloride, and sulfate for the wells and springs sampled each year are shown in the report published each year. Historical data for other constituents for all the wells and springs are available from the USGS water-quality data base or can be found in past reports.

Water from Wells Completed in the N Aquifer

In 1999, water samples were collected from 12 wells completed in the N aquifer. Ten of the wells are in confined parts of the aquifer, one well (Dennehotso PM2) is in an unconfined part, and one well (Red Lake PM1) is on the boundary between the confined and unconfined parts (fig. 9).

The primary types of water in the N aquifer are calcium bicarbonate and sodium bicarbonate. Calcium bicarbonate water generally is in the recharge areas of the northern and northwestern parts of the Black Mesa area, and sodium bicarbonate water is in the area that is downgradient to the south and east. This distribution was found in the water samples collected from the 12 wells in 1999; samples from Kayenta PM2 in the north and from Red Lake PM1 in the northwest were calcium bicarbonate water and samples from the other 10 wells were sodium bicarbonate water (figs. 11 and 12).

Dissolved-solids concentrations in water from the 12 wells ranged from 91 mg/L at Red Lake PM1 to 630 mg/L at Rough Rock PM5 (table 13, fig. 12). Two of the 12 wells had high concentrations of dissolved solids and chloride. Keams Canyon PM2 had a dissolved-solids concentration of 595 mg/L and a chloride concentration of 97 mg/L, and Rough Rock PM5 had a dissolved-solids concentration of 630 mg/L and a chloride concentration of 130 mg/L. Concentrations of

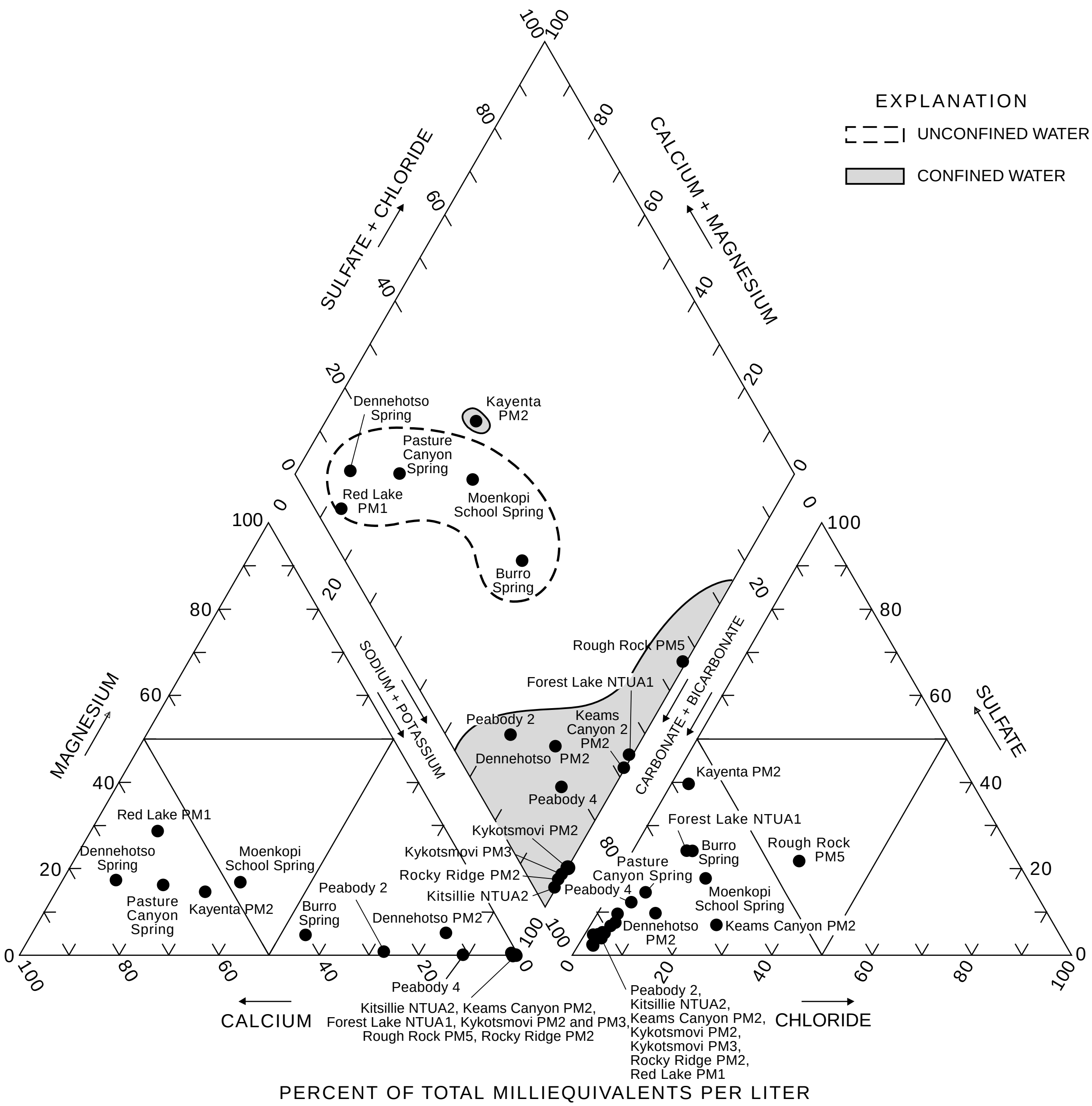


Figure 11. Relative compositions of ground water from the N aquifer, Black Mesa area, Arizona, 1999.

dissolved solids in water samples from the other 10 wells ranged from 91 to 274 mg/L, and concentrations of chloride ranged from 1.4 to 16 mg/L. The areal distribution of dissolved solids generally was similar to the distribution of water types. Lower concentrations of dissolved solids are in the recharge areas of the north and northwest, and higher concentrations of dissolved solids are in areas to the south and east (fig. 12).

Water-chemistry data are available for nine wells and four springs from about the mid-1980’s (table 14, fig. 13). For that time period, the data from those sites have remained fairly stable. In eight of the wells, small year-to-year variations occurred in concentrations of dissolved solids, chloride, and sulfate; however, increasing or decreasing trends are not apparent. In the Forest Lake NTUA 1 well, the chemistry of water

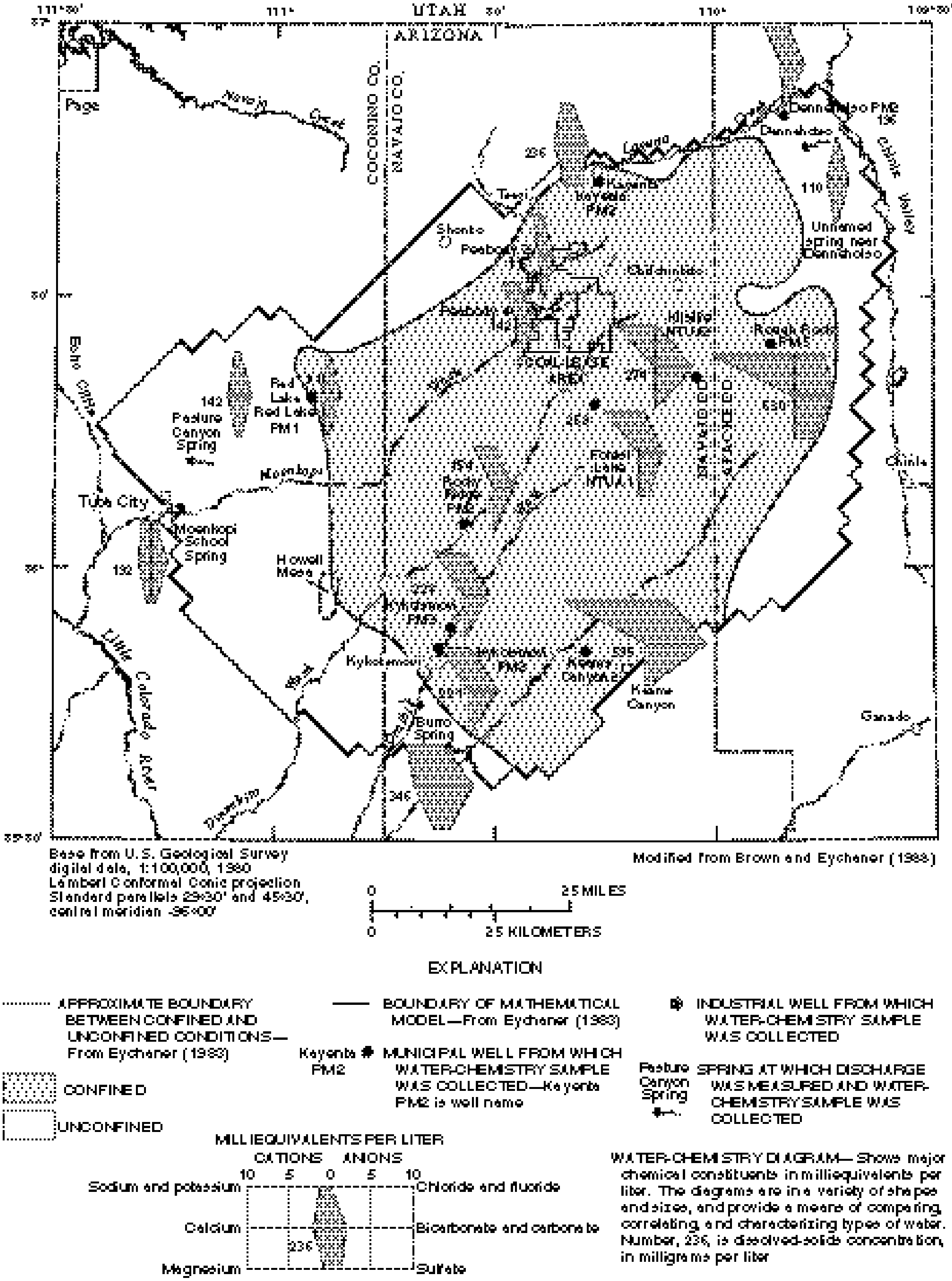


Figure 12. Water chemistry and distribution of dissolved solids in the N aquifer, Black Mesa area, Arizona, 1999.

Table 13. Physical properties and chemical analyses of water from selected industrial and municipal wells completed in the N aquifer, Black Mesa area, Arizona, 1999

[°C, degrees Celsius; µS/cm, microsiemens per centimeter at 25°C; mg/L, milligrams per liter; µg/L, micrograms per liter; <, less than. Dashes indicate no data]

Well name	U.S. Geological Survey identification number	Date of sample	Temperature, field (°C)	Specific conductance, field (µS/cm)	pH, field (units)	Alkalinity, field (mg/L as $CaCO_3$)	Nitrogen NO_2+NO_3 dissolved (mg/L as N)	Phosphorus, ortho, dissolved (mg/L as P)	Calcium, dissolved (mg/L as Ca)	Magnesium, dissolved (mg/L as Mg)
Dennehotso PM2	365045109504001	12–15–99	---	314	9.1	140	1.5	<0.01	7.8	1.9
Forest Lake NTUA1	361737110180301	12–07–99	28.0	380	9.4	140	.57	<.01	.80	.10
Kayenta PM2	364344110151201	12–14–99	15.5	364	8.0	110	.95	<.01	41	6.4
Keams Canyon PM2	355023110182701	12–09–99	18.8	1,040	9.1	370	<.05	<.01	.86	.24
Kitsillie NTUA 2	362043110030501	01–13–00	28.8	454	9.2	220	1.4	.07	.53	<.014
Kykotsmovi PM2	355215110375001	12–06–99	22.5	317	9.7	170	1.2	.04	.50	.03
Kykotsmovi PM3	355236110364501	12–06–99	22.1	340	9.7	160	1.2	.02	.33	<.014
Peabody 2	363005110250901	12–16–99	30.6	167	8.6	78	.99	<.01	8.6	.13
Peabody 4	362901110234101	12–16–99	31.3	216	9.0	90	1.0	<.01	4.5	.03
Red Lake PM1	360527110122501	12–13–99	16.3	153	8.2	78	1.3	<.01	17	5.2
Rocky Ridge PM2	360418110352701	12–08–99	26.6	241	9.4	120	1.3	.02	.40	<.014
Rough Rock PM5	362418109514601	12–14–99	20.7	1,050	8.9	230	1.0	.02	1.9	.26

Well name	Sodium, dissolved (mg/L as Na)	Potassium, dissolved (mg/L as K)	Chloride, dissolved (mg/L as Cl)	Sulfate, dissolved (mg/L as SO_4)	Fluoride dissolved (mg/L as F)	Silica, dissolved (mg/L as SiO_2)	Arsenic, dissolved (µg/L as As)	Boron, dissolved (µg/L as B)	Iron, dissolved (µg/L as Fe)	Dissolved solids, residue at 180°C (mg/L)
Dennehotso PM2	62	0.69	14	15	0.16	13	6	38	<10	196
Forest Lake NTUA1	97	.61	16	49	.42	23	3	125	55	259
Kayenta PM2	25	1.1	4.0	72	.11	18	2	23	<10	236
Keams Canyon PM2	223	.76	97	35	1.5	13	40	642	<10	595
Kitsillie NTUA 2	97	.55	4.0	4.1	.22	28	4	47	<10	274
Kykotsmovi PM2	78	.35	3.5	7.9	.16	27	5	27	<10	221
Kykotsmovi PM3	81	.35	4.3	9.1	.21	26	7	35	<10	228
Peabody 2	27	.68	2.3	8.1	<.10	24	3	<16	<10	115
Peabody 4	42	.63	4.0	13	.15	24	3	18	<10	142
Red Lake PM1	4.4	1.9	1.6	2.1	.13	12	<.9	<16	<10	91
Rocky Ridge PM2	54	.39	1.4	5.3	.11	22	3	20	<10	154
Rough Rock PM5	230	1.2	130	110	1.7	13	48	401	16	630

Table 14. Specific conductance and concentrations of selected chemical constituents in water from industrial and municipal wells completed in the N aquifer, Black Mesa area, Arizona, 1964–99

[μS/cm, microsiemens per centimeter at 25°C; °C, degrees Celsius; mg/L, milligrams per liter. Dashes indicate no data]

Year	Specific conductance, field (μS/cm)	Dissolved solids, residue at 180°C (mg/L)	Chloride, dissolved (mg/L as Cl)	Sulfate, dissolved (mg/L as SO_4)
Dinnehotso PM2				
1964	350	---	12	31
1992	226	131	9.8	19
1993	298	164	8.2	16
1997	[1]305	190	11	14
1999	314	196	14	15
Forest Lake NTUA 1				
1982	470	---	11	67
1990	375	226	8.2	38
1991	[1]350	183	10	24
1993	693	352	35	88
1994	[1]734	430	56	100
1995	470	274	13	60
Do	1,030	626	86	160
Do	488	316	16	71
1996	684	368	44	79
1997	[1]1,140	714	78	250
1998	489	350	37	71
1999	380	259	16	49
Kayenta PM2				
1982	360	([2])	4.5	58
1983	375	([2])	5.9	60
1984	[1]370	209	4.2	51
1986	300	181	8.2	30
1988	358	235	3.8	74
1992	383	210	5.6	78
1993	374	232	3.7	78
1994	[1]371	236	4.2	77
1995	371	250	4.2	72
1996	370	238	3.8	76
1997	[1]379	230	3.9	77
1998	349	236	3.7	71
1999	364	236	4.0	72
Keams Canyon PM2				
1982	1,010	([2])	94	35
1983	1,120	([2])	120	42
1984	[1]1,060	578	96	36
1988	1,040	591	97	34
Keams Canyon PM2--Continued				
1990	1,030	600	94	34
1992	[1]1,010	570	93	36
1993	1,040	590	92	36
1994	[1]975	562	86	32
1995	1,010	606	99	32
1996	1,030	596	96	34
1997	[1]1,070	590	96	33
1998	908	558	78	29
1999	1,040	595	97	35
Kitsillie NTUA 2				
1997	[1]524	269	3.6	4.3
1998	379	270	3.8	4.1
1999	454	274	4.0	4.1
Kykotsmovi PM2				
1988	368	212	3.2	8.6
1990	355	255	3.2	9.0
1991	[1]374	203	4.4	7.9
1992	363	212	3.3	8.4
1994	[1]365	212	3.6	8.5
1995	368	224	3.1	6.2
1996	365	224	3.3	8.5
1997	[1]379	222	3.0	8.0
1998	348	223	3.3	7.3
1999	317	221	3.5	7.9
Kykotsmovi PM3				
1998	341	219	4.6	8.4
1999	340	228	4.3	9.1
Peabody 2				
1980	225	145	11	20
1986	172	---	2.6	8.1
1987	149	113	5.0	9.1
1993	163	124	1.7	8.9
1998	93	119	2.2	7.9
1999	167	115	2.3	8.1
Peabody 4				
1974	200	140	3.8	13
1975	220	144	3.4	13

See footnotes at end of table.

Table 14. Specific conductance and concentrations of selected chemical constituents in water from industrial and municipal wells completed in the N aquifer, Black Mesa area, Arizona, 1964–99—Continued

Year	Specific conduct-ance, field (μS/cm)	Dissolved solids, residue at 180°C (mg/L)	Chlo-ride, dis-solved (mg/L as Cl)	Sulfate, dis-solved (mg/L as SO_4)	Year	Specific conduct-ance, field (μS/cm)	Dissolved solids, residue at 180°C (mg/L)	Chlo-ride, dis-solved (mg/L as Cl)	Sulfate, dis-solved (mg/L as SO_4)
Peabody 4—Continued					**Rocky Ridge PM2**				
1976	240	138	2.9	19	1986	247	164	2.4	6.4
1979	220	---	3.9	19	1998	215	140	1.4	<.10
1980	230	139	4.3	13	1999	241	154	1.4	5.3
1986	205	---	4.2	12	**Rough Rock PM5**				
1987	194	135	[3]5.0	13	1983	1,090	([2])	130	110
1992	224	125	4.3	12	1984	[1]1,100	613	130	99
1993	214	124	[3]3.0	12	1986	1,010	633	140	120
1996	214	140	3.8	12	1988	1,120	624	130	[3]110
1997	[1]203	139	3.5	12	1991	[1]1,210	574	130	110
1999	216	142	4.0	13	1993	1,040	614	130	110
Red Lake PM1					1994	[1]1,070	626	130	110
1992	164	87	2.6	1.9	1995	1,110	648	140	110
1993	156	84	1.6	2.1	1996	1,100	634	130	110
1995	157	92	1.6	2.0	1997	[1]1,060	628	130	110
1997	[1]156	96	3.2	1.7	1998	894	637	130	110
1999	153	91	1.6	2.1	1999	1,050	630	130	110

[1]Value shown in Black Mesa monitoring reports from previous years for this date is different. The earlier reports showed values determined by laboratory analysis.
[2]Value shown in Black Mesa monitoring reports from previous years for this date is different. The earlier reports showed values determined by the sum of constituents.
[3]Value shown in Black Mesa monitoring reports from previous years for this date is different. The earlier reports applied a different rounding method.

samples has varied considerably between 1982 and 1999. Concentrations of dissolved solids, chloride, and sulfate increased from 1982 to 1997 and decreased in 1998 and 1999.

Comparison of the water samples from the 12 wells with U.S. Environmental Protection Agency (USEPA) Primary and Secondary Drinking-Water Regulations showed that the concentrations of most of the analyzed constituents were below Maximum Contaminant Levels (MCL's) and Secondary Maximum Contaminant Levels (SMCL's; U.S. Environmental Protection Agency, 2000). pH, however, exceeded the SMCL in samples from 10 of the 12 wells. The upper SMCL for pH is 8.5 units (table 13). SMCL's provide guidelines for the control of contaminants that may cause cosmetic effects (such as skin or tooth discoloration) or aesthetic effects (such as taste, odor, or color) in drinking water. The USEPA recommends SMCL's for water systems; however, compliance with these SMCL's is not mandatory.

Samples from two of the 12 wells had concentrations of other constituents that exceeded an SMCL and a proposed MCL. The water samples from Keams Canyon PM2 and Rough Rock PM5 had dissolved-solids concentrations higher than the

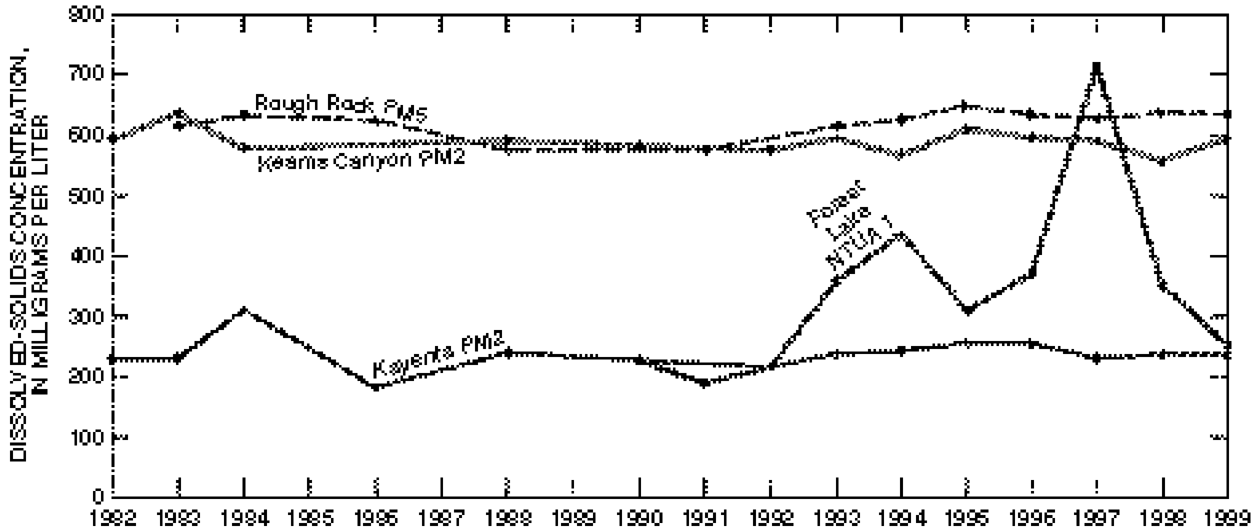


Figure 13. Dissolved-solids concentrations in water from wells Keams Canyon PM2, Rough Rock PM5, Forest Lake NTUA 1, and Kayenta PM2, Black Mesa area, Arizona, 1982–99.

applicable SMCL (500 mg/L; table 13). Those two water samples also had high concentrations of arsenic. The sample from Keams Canyon PM2 had a concentration of 40 µg/L, and the sample from Rough Rock PM5 had a concentration of 48 µg/L. The existing USEPA MCL for arsenic is 50 µg/L; however, the USEPA has proposed a new standard of 5 µg/L. The new MCL for arsenic will become effective on January 1, 2001, after a comment period from June 22, 2000, to January 1, 2001. The new MCL for arsenic may not be 5 µg/L; however, there is a high probability that it will be closer to 5 µg/L than to 50 µg/L. MCL's established by the USEPA are legally enforceable standards.

Water from Springs that Discharge from the N Aquifer

In 1999, water samples were collected from four springs in the study area. Burro Spring is on the south side of the study area, an unnamed spring near Dennehotso is on the northeast side, and Moenkopi School Spring and Pasture Canyon Spring are on the west side (fig. 9). All the springs discharge water from the unconfined part of the N aquifer.

Water samples from three of the springs—Pasture Canyon Spring, Moenkopi School Spring, and an unnamed spring near Dennehotso—were a calcium carbonate type and had low dissolved-solids concentrations (110 to192 mg/L). The water sample from Burro Spring was a sodium carbonate type and had a much higher dissolved-solids concentration of 346 mg/L (table 15, fig. 12). Concentrations of analyzed constituents in samples from the four springs were below current MCL's and SMCL's (U.S. Environmental Protection Agency, 2000).

From the early 1980's to 1999, trends were not apparent in the concentrations of dissolved solids, chloride, and sulfate in water samples from Burro Spring, an unnamed spring near Dennehotso, and Pasture Canyon Spring. From 1987 to 1999, a slight increasing trend is apparent in the concentrations of those constituents in water samples from Moenkopi School Spring (table 16).

Table 15. Physical properties and chemical analyses of water from selected springs that discharge from the N aquifer, Black Mesa area, Arizona, 1999

[°C, degree Celsius; µS/cm, microsiemens per centimeter at 25°C; mg/L, milligrams per liter; µg/L, micrograms per liter; <, less than. Dashes indicate no data]

Spring name	Bureau of Indian Affairs site number	U.S. Geological Survey identification number	Rock formation	Date of sample	Temperature (°C)	Specific conductance, field (µS/cm)	pH (units)	Alkalinity (mg/L as $CaCO_3$)	Nitrogen, NO_2+NO_3, dissolved (mg/L as N)	Phosphorus, ortho, dissolved (mg/L as P)
Burro Spring	6M-31	354156110413701	Navajo Sandstone	12–07–99	---	545	8.1	190	0.27	<0.01
Unnamed spring near Dennehotso	8A-224	364656109425400	Navajo Sandstone	12–15–99	7.7	184	7.8	80	1.6	.01
Moenkopi School Spring	3GS–77–6	360632111131101	Navajo Sandstone tongue in the Kayenta Formation	12–13–99	17.5	305	7.6	---	2.4	<.01
Pasture Canyon Spring	3A-5	361021111115901	Navajo Sandstone	12–21–99	15.3	235	7.7	81	4.6	.02

Spring name	Hardness (mg/L as $CaCO_3$)	Hardness, noncarbonate (mg/L as $CaCO_3$)	Calcium, dissolved (mg/L as Ca)	Magnesium, dissolved (mg/L as Mg)	Sodium, dissolved (mg/L as Na)	Sodium adsorption ratio	Percent sodium	Sodium plus potassium, dissolved (mg/L as Na+K)	Potassium, dissolved (mg/L as K)	Chloride, dissolved (mg/L as Cl)
Burro Spring	130	---	46	3.0	72	3	55	72	0.50	25
Unnamed spring near Dennehotso	81	---	26	3.8	4.3	.2	10	5.4	1.1	2.8
Moenkopi School Spring	98	---	29	6.2	25	1	35	26	1.4	19
Pasture Canyon Spring	90	---	29	4.4	11	.5	20	12	1.4	5.1

Spring name	Sulfate, dissolved (mg/L as SO_4)	Fluoride, dissolved (mg/L as F)	Silica, dissolved (mg/L as SiO_2)	Arsenic, dissolved (µg/L as As)	Boron, dissolved (µg/L as B)	Iron, dissolved (µg/L as Fe)	Dissolved solids, residue at 180°C (mg/L)
Burro Spring	69	0.45	14	1	72	<10	346
Unnamed spring near Dennehotso	6.3	.10	13	3	<16	<10	110
Moenkopi School Spring	26	.13	15	2	31	<10	192
Pasture Canyon Spring	14	.16	10	2	32	<10	142

Table 16. Specific conductance and concentrations of selected chemical constituents in water from selected springs that discharge from the N aquifer, Black Mesa area, Arizona, 1948–99

[µS/cm, microsiemens per centimeter at 25°C; mg/L, milligrams per liter; °C, degrees Celsius. Dashes indicate no data]

Year	Specific conductance, field (µS/cm)	Dissolved solids, residue at 180°C (mg/L)	Chloride, dissolved (mg/L as Cl)	Sulfate, dissolved (mg/L as SO_4)
Burro Spring				
1989	485	308	22	59
1990	[1]545	347	23	65
1993	595	368	30	85
1994	[1]597	368	26	80
1996	525	324	23	62
1997	[1]511	332	26	75
1998	504	346	25	70
1999	545	346	25	69
Unnamed spring near Dennehotso				
1984	195	112	2.8	7.1
1987	178	[2]109	3.4	7.5
1992	178	108	3.6	7.3
1993	184	100	3.2	8
1995	184	124	2.6	5.7
1996	189	112	2.8	8.2
1997	[1]170	98	2.4	6.1
1998	179	116	2.4	5.4
1999	184	110	2.8	6.3
Moenkopi School Spring				
1952	222	---	6	---
1987	270	161	12	19
1988	270	155	12	19
1991	297	157	14	20
1993	313	204	17	27
1994	305	182	17	23
1995	314	206	18	22
1996	332	196	19	26
1997	[1]305	185	18	24
1998	296	188	18	24
1999	305	192	19	26
Pasture Canyon Spring				
1948	[1]227	([2])	5	13
1982	240	---	5.1	18
1986	257	---	5.4	19
1988	232	146	5.3	18
1992	235	168	7.1	17
1993	242	134	5.3	17
1995	235	152	4.8	14
1996	238	130	4.7	15
1997	232	143	5.3	17
1998	232	147	5.1	16
1999	235	142	5.1	14

[1]Value shown in Black Mesa monitoring reports from previous years for this date is different. The earlier reports showed values determined by laboratory analysis.

[2]Value shown in Black Mesa monitoring reports from previous years for this date is different. The earlier reports showed values determined by the sum of constituents.

SUMMARY

The N aquifer is the major source of water for industrial and municipal users in the Black Mesa area of northeastern Arizona. Availability of water is an important issue in the Black Mesa area because of continued industrial and municipal use, a growing population, and a precipitation of only about 6 to 12 in./yr.

In 1999, total ground-water withdrawals were 7,110 acre-ft, industrial use was 4,210 acre-ft, and municipal use was 2,900 acre-ft. From 1998 to 1999, total withdrawals increased by 0.7 percent, industrial use increased by 4 percent, and municipal use decreased by 4 percent. During the past 10 years, total withdrawals and municipal and industrial use increased at an average rate of about 2 percent per year.

Flowmeters attached to 25 municipal wells were tested for accuracy with a test mechanical flowmeter. Twenty-four wells had flowmeter readings within 10 percent of the test meter. The flowmeter reading at one well was within 12.2 percent of the test-meter reading.

From 1998 to 1999, ground-water levels declined in 25 of 31 wells. The median water-level change in the 31 wells was a decline of 0.8 ft, and changes ranged from a decline of 18.7 ft to a rise of 8.9 ft. In unconfined areas, water levels declined in 11 of 15 wells, and the median change was a decline of 0.7 ft. In confined areas, water levels declined in 14 of 16 wells, and the median change was a decline of 1.2 ft.

From 1998 to 1999, the water levels declined by a median of 0.7 ft in unconfined areas; however, the average annual median change from 1983 to 1999 was +0.2 ft. The median decline of 1.2 ft in confined areas was a slightly smaller decline than the average annual median decline of 1.9 ft.

From the prestress period (prior to 1965) to 1999, water levels in the 31 wells declined by a median of 10.6 ft. Water levels in the 15 wells in the unconfined part of the aquifer had a median change of 0.0 ft and ranged from a decline of 38 ft to a rise of 14 ft. Water levels in the 16 wells in the confined part of the aquifer had a median decline of 45.5 ft and ranged from a decline of 174.8 ft to a rise of 0.6 ft.

Discharges were measured annually at four springs in 1998 and 1999. Burro Spring had no changes in discharge, an unnamed spring near Dennehotso had a 30-percent decrease, Moenkopi School Spring had an 11-percent increase, and Pasture Canyon Spring had a 3-percent decrease. For about the past 10 years, discharges in the four springs have fluctuated; however, increasing or decreasing trends are not apparent.

The annual average discharges for the four streamflow-gaging stations vary considerably during their periods of record; therefore, it is difficult to discern any trends. Continuous records of surface-water discharge have been collected from July 1976 to 1999 at Moenkopi Wash, July 1976 to 1999 at Laguna Creek, June 1993 to 1999 at Dinnebito Wash, and April 1994 to 1999 at Polacca Wash. Median flows for November, December, January, and February of each water year are used as an index of ground-water discharge to those streams. Increasing or decreasing trends are not apparent in these median winter flows for the periods of record.

In 1999, water samples were collected from 12 wells and analyzed for selected chemical constituents. Dissolved-solids concentrations ranged from 91 to 630 mg/L, and samples from 10 of the 12 wells had dissolved-solids concentrations less than 275 mg/L. Water-chemistry data are available for nine wells and four springs from about the mid-1980’s. For that time period, the data from those sites have remained fairly stable.

Dissolved-solids concentrations in water samples from an unnamed spring near Dennehotso, Pasture Canyon Spring, and Moenkopi School Spring ranged from 110 to 192 mg/L, and dissolved-solids concentration in the water sample from Burro Spring was 346 mg/L. Trends are not apparent in the concentrations of dissolved solids, chloride, and sulfate from the early 1980’s to 1999 at Burro Spring, an unnamed spring near Dennehotso, and Pasture Canyon Spring. From 1987–99, concentrations of those constituents appear to be increasing slightly at Moenkopi School Spring.

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